Deep-water polygonal fault systems as terrestrial analogs for large-scale Martian polygonal terrains

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ABSTRACT

Discovery of giant polygonal terrains on Mars has prompted a 30-year debate over how they formed. The prevailing hypothesis is that small-scale Martian polygons formed by thermal contraction, as in terrestrial permafrost environments. Large-scale (>1 km) Martian polygons in the northern plains are visible in THEMIS, MOLA, *Viking*, and *Mariner* data, but how they formed remains enigmatic. We suggest that terrestrial deep-water marine polygons are morphological and perhaps genetic analogs to large-scale Martian polygonal features. The terrestrial, deep-water polygons are imaged in three-dimensional seismic-reflection data acquired by the oil and gas industry in offshore Norway and the Gulf of Mexico.

How deep-water polygonal fault systems form is a debated topic beyond the scope of this work. However, similarities between terrestrial deep-water polygonal fault systems and large-scale Martian polygonal terrains suggest that the latter could have formed during deep-water marine deposition. Deep-water polygonal faults form within fine-grained sediment at shallow burial depths. Increases in slope angles can trigger downslope disaggregation of deep-water polygons and mass wasting (forming debris flows). Physical models indicate that multidirectional extension can cause polygonal features to break up on a slope over a mobile substrate. Some knobby terrains in the Vastitas Borealis Formation seem to originate from disaggregation of large-scale Martian polygonal terrains. These analogies suggest a possible deep-water subaqueous origin for large-scale Martian polygonal terrains and support the idea of a late Hesperian–early Amazonian ocean on the northern plains of Mars.

INTRODUCTION

Polygonal terrains on Mars cover a wide spectrum of scales (Levy et al., 2009; Hiesinger and Head, 2000) and have been linked to a variety of processes, including basalt loading, cooling of volcanic material, tectonic deformation, desiccation, density-driven convection, and thermal contraction (McGill, 1986; McGill and Hills, 1992; Hiesinger and Head, 2000; Buczkowski and McGill, 2002; Buczkowski and Cooke, 2004; Levy et al., 2010). Several decades of detailed observations of the Martian surface have allowed researchers to conclude that small-scale Martian polygons (typically <25 m in diameter) can form by thermal contraction processes similar to those in terrestrial permafrost environments (Mutch et al., 1977; Mellon, 1997; Head et al., 2003; Levy et al., 2008). However, formation of large-scale Martian polygons (hundreds of meters to kilometers in diameter) (Fig. 1) is not well explained by permafrost processes and remains highly speculative (Lane and Christensen, 2000; Hiesinger and Head, 2000; Cooke et al., 2011). Lane and Christensen (2000) postulated that Rayleigh free convection within a thick, catastrophic flood deposit on the northern plains of Mars formed large-scale polygonal terrains. In contrast, Hiesinger and Head (2000) proposed that tectonic uplift of an ancient Martian basin floor was the ultimate trigger for forming large-scale Martian polygons. Most recently, Cooke et al. (2011) suggested that giant polygons in Utopia Planitia formed by volumetric compaction of wet, fine sediments along the slopes of buried basement in an ancient Martian ocean. We support the idea that large-scale Martian polygons on the northern plains of Mars formed in deep water in a late Hesperian–Amazonian ocean (Lucchitta et al., 1986; Baker et al., 1991; Parker et al., 1989, 1993; Head et al., 1999; Cooke et al., 2011). We strengthen the argument by presenting striking geomorphological similarities between terrestrial deep-water, polygonal fault systems and what we consider to be their Martian counterparts (Figs. 1–3). We use recently acquired high-resolution, three-dimensional seismic data from offshore Norway and the Gulf of Mexico to document in detail the geomorphology of deep-water polygonal systems.

Seismic surveys have greatly improved our ability to study terrestrial deep-water environments (Cartwright et al., 2003) (Figs. 2 and 3) and made available analogs that might be relevant to past Martian environments (Moscardelli and Wood, 2011; Burr, 2011). More than 20 examples of terrestrial, kilometer-scale, marine polygonal fault systems have been studied on passive margins or within cratons (Cartwright and Dewhurst, 1998). On Earth, the genesis of deep-water polygonal faults has been attributed to a variety of mechanisms, including gravity collapse, density inversion, syneresis, gravitational loading, fluid expulsion, low coefficients of residual friction, and diagenesis (Cartwright et al., 2003; Goulty and Swarbrick, 2005; Goulty, 2008; Cartwright, 2011). The specific physical or chemical processes that created large polygons on Earth or Mars are beyond the scope of this paper, however, and the reader is referred to Hiesinger and Head (2000), Cartwright et al. (2003), and Cartwright (2011) for summaries. Our paper (1) provides a deep-water terrestrial analog that might help elucidate the environment of deposition of large-scale Martian polygonal terrains; (2) illustrates geomorphological complexities within deep-water environments and applies these to Mars; and (3) highlights how modern seismic data from industry can elucidate purely academic problems in deep-water environments and on other planets.

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DEEP-WATER POLYGONAL FAULT SYSTEMS ON EARTH

Polygonal fault systems are widespread in the North Sea and the Norwegian Sea (Cartwright and Dewhurst, 1998). Deep-water polygonal faults form in marine sediments having high porosities and low permeabilities; these are commonly but not exclusively composed of ultrafine-grained smectitic claystones or carbonate chalks (Cartwright and Dewhurst, 1998). Deep-water polygonal systems within units that have diverse mineralogy suggest that particle size might be more important than composition in their formation, but lithology also plays a crucial role. Figure 2 shows seismically imaged polygonal faults from the deep-water (>500 m) eastern margin of the Vøring Basin in offshore Norway. The Eocene–Oligocene Brygge Formation is clay-rich and has an average thickness of 450 m (Fig. 2A). Near its base, polygons reach 1 km in diameter (Fig. 2B). Higher in the unit, polygons are smaller and more abundant (Fig. 2C). Deep-water polygonal faults such as these are attributed mainly to syneresis, low coefficients of

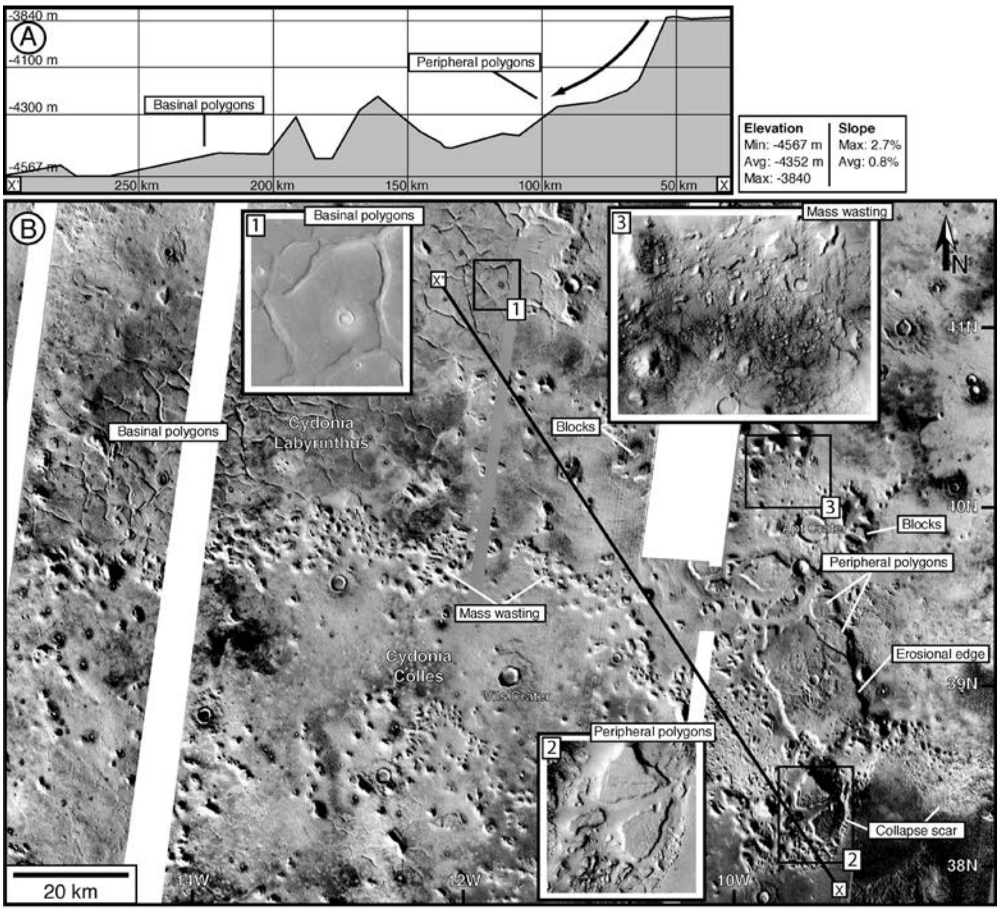

Figure 1. (A) Profile using THEMIS and MOLA imagery showing topographic differences between areas of large-scale Martian peripheral and basinal polygons in Acidalia Planitia. This profile was used to calculate maximum (2.7%) and average (0.8%) slope values. (B) Map showing basinal and peripheral polygons in Acidalia Planitia.

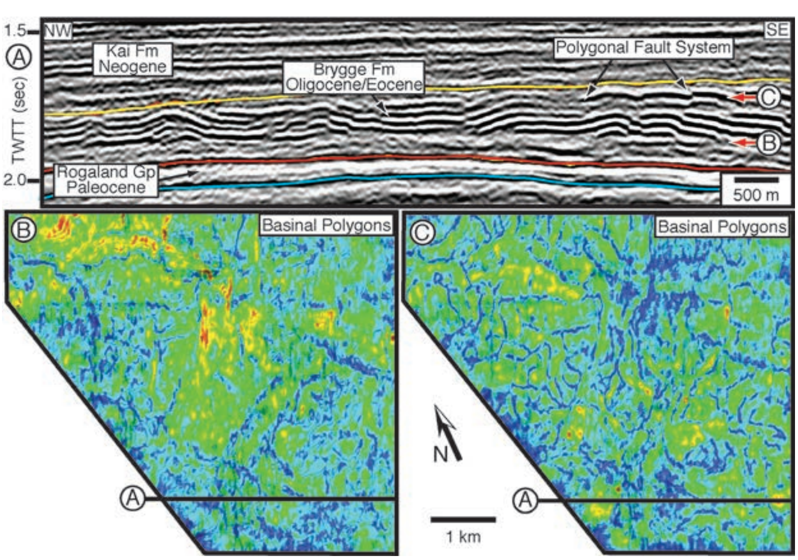

Figure 2. Seismic profile and maps of root mean square of the seismic wave amplitudes showing two levels of a deep-water polygonal fault system within the Eocene-Oligocene Brygge Formation (offshore Norway). Seismic data courtesy of the Norwegian Petroleum Directorate. TWTT—two-way travel time.

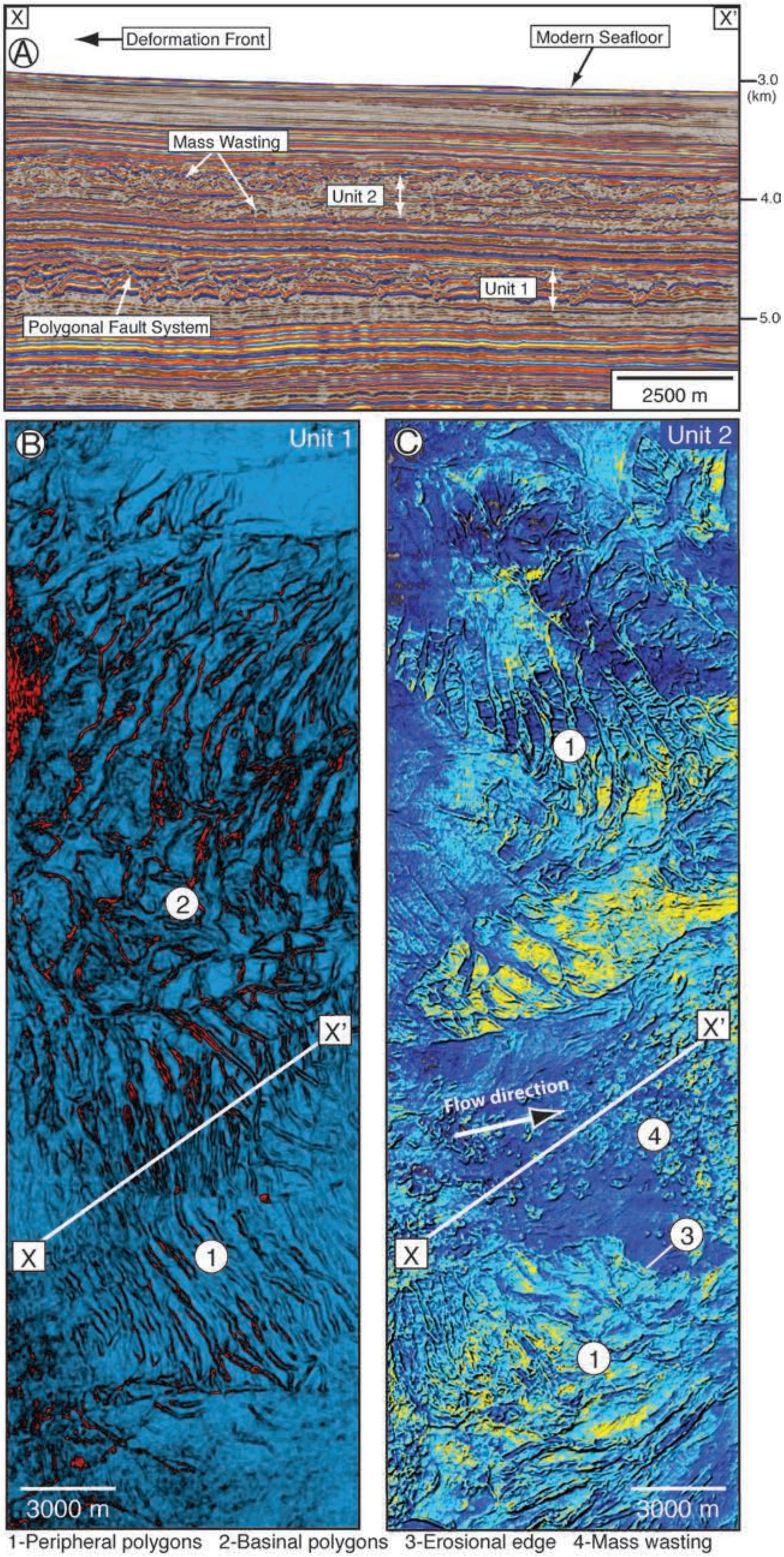

Figure 3. (A) Seismic profile, (B) semblance attribute map, and (C) spectral decomposition map on two different deep-water polygonal fault systems within Cenozoic strata of the northern Gulf of Mexico. Semblance attributes measure lateral changes in the seismic response caused by variations in structure and stratigraphy. Spectral decomposition breaks the seismic signal into its dominant frequency components to highlight structural and stratigraphic features. Seismic data courtesy of CGGVeritas.

friction, or diagenetically induced shear failure (Cartwright et al., 2003; Goulty, 2008; Cartwright, 2011). Most of the mechanisms envisaged act soon after deposition or at shallow burial depths (Cartwright et al., 2003; Goulty, 2008; Cartwright, 2011). Syneresis is the subaqueous contraction of gels in flocculating clays as water is lost by compaction or by an increase in salinity. The high clay content in the Brygge Formation could form gels during deposition because of the micron size of its particles, so syneresis is theoretically feasible (Cartwright et al., 2003). Goulty (2008) suggested instead that low coefficients of residual friction in fine-grained sediments are the key to the development of deep-water polygonal faults. However, residual friction only applies after initial slip occurs, so what triggered the faults remains obscure (Goulty, 2008). Recent experimental work (Shin et al., 2008) provides an alternative explanation in which diagenesis of clay-rich sediments can lead to shear failure under low confining stresses, triggering the formation of polygonal fault systems (Cartwright, 2011). Regardless of the genetic mechanism, there is a consensus that deep-water polygonal faults typically form (1) in sequences of very fine grained sediments; (2) in marine basins of >500 m water depth; and (3) at shallow burial depths (Cartwright et al., 2003; Goulty, 2008). Some deep-water polygonal faults in the Vøring Basin have sea-floor expression (Cartwright et al., 2003, their figure 15), indicating that thick overburdens are not necessary to form the polygonal pattern (Cartwright and Dewhurst, 1998; see their figure 10).

Another example of deep-water polygonal fault systems is observed seaward of the Sigsbee Escarpment, which marks the limit of shallow salt canopies in the Gulf of Mexico (Fig. 3). The Neogene polygonally faulted units there have an average thickness of 500 m (Fig. 3A), and the polygons can be more than 3 km wide (Fig. 3B). Onlaps and truncations by overlying units indicate that these polygons formed shortly after sediments were deposited in the basin at water depths that exceeded 1000 m. Unit 1 formed when the canopy front was 4 km north of the northern edge of visible polygons. A map (Fig. 3B) shows the typical interlocking shapes of deep-water polygons. However, faults located next to the main polygons have a strong northeast strike in response to advance of the salt canopy and subsequent southward

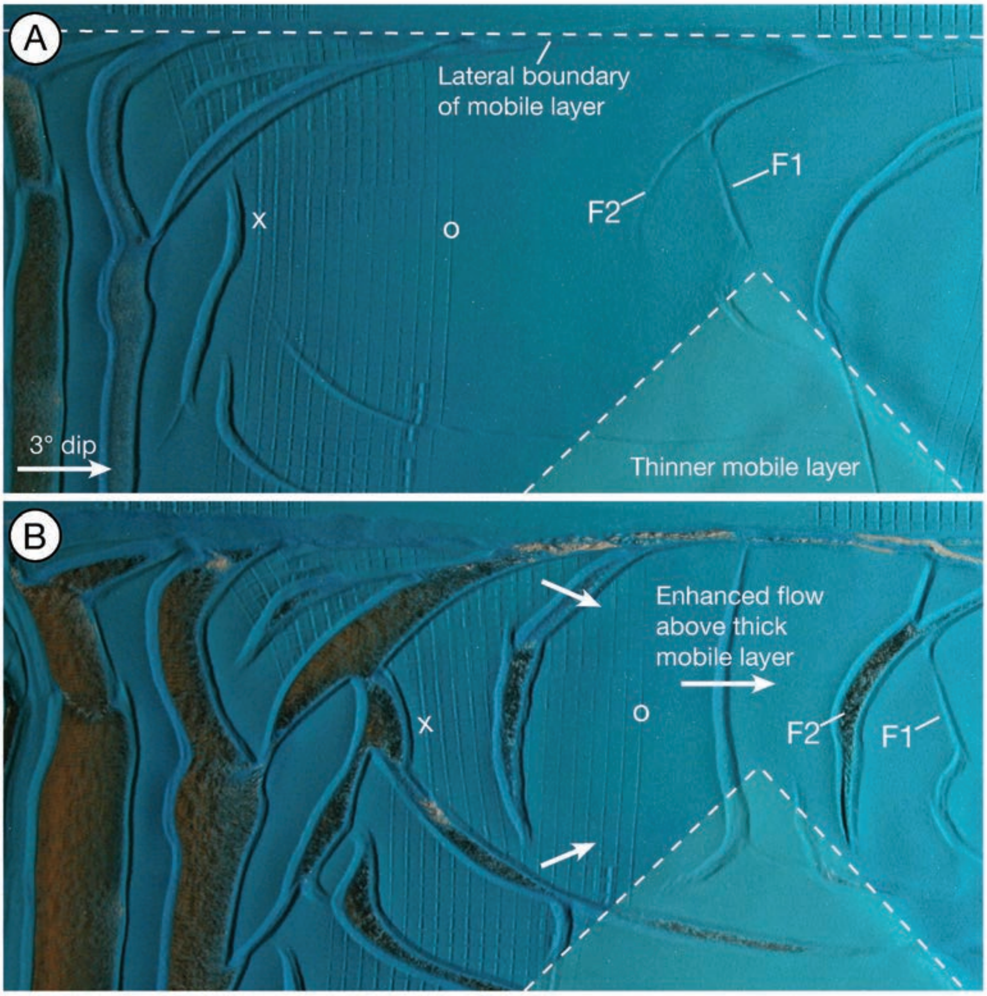

Figure 4. Physical model showing transition from (A) normal faulting to (B) separated polygons under multidirectional extension triggered by gravity. The model comprises a brittle layer of dry blue sand overlying a viscous layer of transparent, colorless silicone polymer (polydimethylsiloxane). Initial fault patterns are controlled by the surface dip of the model and the lateral boundaries of the mobile unit (A). Thickness variations within the mobile unit result in multidirectional extension due to enhanced flow within the thicker mobile unit, separating and rotating the polygons (B). F1 and F2—faults; x and o—arbitrary marker points.

tilting of the seafloor. Unit 2 formed when the canopy front had advanced 1 km closer, building a steeper slope that disrupted the polygonal blocks and caused downslope mass wasting as debris flows (Fig. 3C). Partly deformed polygons within unit 2 record a stage of disruption intermediate between intact glide blocks and debris flows (Fig. 3C). Deep-water polygonal faults are commonly associated with mass wasting units (slides, slumps, and debris flows) (Fig. 3C) (Cartwright, 2011). Numerical models show that buried topography can control the geometry of giant polygons during the faulting (Cooke et al., 2011). A physical model simulates a later stage where the polygons are disrupted. The physical model shows how gravity gliding alone can radically deform polygonal fault systems if a brittle, faulted layer overlies a mobile substratum and both are gently tilted (Fig. 4A). The pattern of extension is strongly influenced by (1) surface dips supplying a gravitational component of shear stress; and (2) thickness variations in the mobile substratum, which cause spatial and temporal variations in the extension rate (Fig. 4B). Thus multidirectional extension in response to surface dip and thickness variations is one way to modify giant polygonal fault systems under gravity on Earth.

SIMILARITIES BETWEEN MARTIAN AND TERRESTRIAL DEEP-WATER POLYGONS

Large-scale polygonal terrains are common on the northern plains of Mars (Fig. 1) in Elysium, Acidalia, and Utopia Planitia (Lucchitta et al., 1986). The diameter of large-scale Martian polygons is variable (1–32 km), as are the widths of troughs defining their polygonal shapes (200–800 m) (Hiesinger and Head, 2000). Large-scale polygons on Mars (Fig. 1) resemble deep-water polygons on Earth (Figs. 2 and 3), especially in the distinction of two types of polygons. Basinal polygons have a uniform pattern, whereas peripheral polygons are more discontinuous and irregular (Figs. 1 and 3). Basinal polygons are present on Mars (Cydonia Labyrinthus in Acidalia Planitia and Utopia Planitia) and Earth (Brygge Formation in offshore Norway; Fig. 2 herein; unit 1 in the Gulf of Mexico; Fig. 3B herein). On Earth, basinal polygons are found where slopes are gentle (<0.5°) and younger deformation is absent, so the original geometry is preserved (Figs. 2 and 3B). On Mars, basinal polygons formed mostly on the northern plains, far from interpreted paleoshorelines or outflow channel outlets (Fig. 1). Peripheral polygons on Earth formed above steeper (>0.5°) slopes affected by gravity-induced sediment deformation (Fig. 3C). Unit 2 in the Gulf of Mexico clearly shows peripheral polygons progressively disrupted to form debris flows (Fig. 3C). Our physical model suggests that peripheral polygons can evolve in a brittle layer under the influence of a surface slope and a mobile substrate of uneven thickness (Fig. 4). Similar peripheral polygons on Mars occur near possible paleoshorelines and within outflow channels (e.g., Chryse and Hydraotes Chaos). Peripheral polygons also occur where slopes are locally steeper (e.g., Acidalia

Mensa and Acidalia Colles) (Fig. 1). The polygonal terrain on the southeast corner of Figure 1B (Acidalia Planitia) resembles that in unit 2 in the Gulf of Mexico (Fig. 3C), where the polygons were disrupted and reduced to mass-wasting deposits, and in the physical model (Fig. 4) in which these polygons were torn apart and rafted under gravity.

DISCUSSION

The origin of small-scale Martian polygons has convincingly been linked to thermal contraction (Mellon, 1997; Levy et al., 2010). However, the origin of large-scale and older Martian polygonal terrains on the northern plains of Mars remains debatable (Hiesinger and Head, 2000; Lane and Christensen, 2000; Cooke et al., 2011). Lucchitta et al. (1986) proposed that large-scale Martian polygonal terrains formed when sediment slurries shed from the highlands were rapidly deposited and froze on an ancient ocean locally covered by ice on the northern plains. Lane and Christensen (2000) suggested that to form a 5-km-diameter Martian polygon, the system would need an ~1.1- to 1.5-km-thick freely convecting layer. This anomalously thick layer could have been a thick, water-saturated, sedimentary package that accumulated rapidly from catastrophic flooding linked to outflow channels (Lane and Christensen, 2000). In Utopia and Acidalia Planitia, these polygons are late Hesperian–Amazonian in age, coeval with outflow channels and the Vastitas Borealis Formation (Lucchitta et al., 1986; Werner et al., 2011). Terrestrial deep-water polygonal faults can develop within hosts up to 1 km thick, but their formation is linked to syneresis, low coefficients of residual friction, and/or diagenetically induced shear failure instead of thermal contraction or convection (Cartwright et al., 2003; Goulty, 2008; Cartwright, 2011). We concur with a subaqueous origin for Martian polygonal terrains (Lucchitta et al., 1986; Cooke et al., 2011), but based on terrestrial analogs (Cartwright et al., 2003; Goulty, 2008), we infer an alternative mechanism that does not require contraction by freezing or upwelling by convection. Recent radar data from the MARSIS/Mars Express indicate that the dielectric constant of the Vastitas Borealis Formation is low enough to be attributed to widespread deposition of aqueous or icy sediments on the northern plains (Mouginot et al., 2012). We infer that Martian polygonal terrains formed shortly after sediments were deposited as sediment slurries on an ocean floor that then rapidly expelled pore fluids. Large-scale Martian polygons then formed subaqueously on this substratum by syneresis (Cartwright et al., 2003; Cooke et al., 2011) in response to low coefficients of friction on fault planes (Goulty, 2008) or by diagenetically induced shear failure (Cartwright, 2011). We agree with the hypothesis of Cooke et al. (2011) that gravitationally induced extension controlled by buried topography influenced the formation of large-scale Martian polygonal terrains. Based on our physical model, we suggest that polygonal terrains can be severely disrupted by extension where surface dips are increased (Fig. 4).

Regardless of how they formed, large-scale Martian basinal polygons are preserved where slopes were low (e.g., Cydonia Labyrinthus and Utopia Planitia) (Fig. 1). Intact, deep-water, polygonal fault systems are also preserved on Earth on gentle slopes (Fig. 2). In contrast, large-scale, Martian peripheral polygons formed near outflow channel outlets where steeper slopes induced gravitational instability (Fig. 1). Deformation of giant Martian polygons due to slope changes can explain why polygonal and knobby terrains commonly coexist in the northern plains (Fig. 1) and in terrestrial deep-water environments (Fig. 3C). Large boulders and rubble piles overlying much of the Vastitas Borealis and Scandia formations have been interpreted as incompatible with marine deposition (McEwen et al., 2007). However, terrestrial deep-water mass-wasting units contain rafted blocks as large as 3 km^2 in area and at least 100 m thick (Macdonald et al., 1993; Dunlap et al., 2010; Jackson, 2011). Mass-wasting in deep water can catastrophically mobilize huge volumes of sediment in highly efficient plastic flows containing both fine-grained and coarse-grained sediments (Moscardelli and Wood, 2008).

CONCLUSIONS

Hiesinger and Head (2000) have argued that deep-water polygonal fault systems are not an appropriate analog for large-scale Martian polygonal terrains because the terrestrial polygons are considerably smaller (<1 km) than those on Mars. The scale of terrestrial deep-water polygons is in fact comparable to that of large-scale Martian polygons (Figs. 2 and 3). Our study and that of Cooke et al. (2011) suggest that deep-water (>500 m) polygonal fault systems are appropriate analogs for large-scale Martian polygons. We infer that large-scale polygonal terrains on the northern plains of Mars most likely formed under deep-marine conditions (>500 m water depth) because of (1) geomorphologic similarities between large-scale Martian polygonal terrains and deep-water polygonal fault systems on Earth; (2) geomorphologic evidence of a late Hesperian–Amazonian ocean on the northern plains of Mars (Baker et al., 1991; Parker et al., 1989, 1993; Head et al., 1999; Clifford and Parker, 2001; Moscardelli and Wood, 2011; Mouginot et al., 2012); (3) the requirement that high volumes of water were needed to form outflow channels (Clifford and Parker, 2001); and (4) similarities between peripheral polygons and polygons formed by multidirectional extension in physical models. Despite the debate concerning the exact genetic mechanism for the formation of terrestrial deep-water polygonal faults, competing hypotheses are compatible with a deep-marine origin (Cartwright et al., 2003; Goulty, 2008; Cartwright, 2011). Additionally, most authors agree that large-scale polygons formed soon after sediment was deposited on both Earth and Mars (Lane and Christensen, 2000; Cartwright et al., 2003; Goulty, 2008; Lucchitta et al., 1986). Irrespective of the mechanisms forming the polygons, these lines of evidence point to a deep-water setting on the northern plains of Mars during late Hesperian–Amazonian times.

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REFERENCES CITED

Baker, V.R., Strom, R.G., Gulick, V.C., Kargel, J.S., Komatsu, G., and Kale, V.S., 1991, Ancient oceans, ice sheets and the hydrological cycle on Mars: Nature, v. 352, p. 589-594, doi: 10.1038/352589a0.

Buczkowski, D.L., and Cooke, M.L., 2004, Formation of double-ring circular grabens due to volumetric compaction over buried impact craters: Implications for thickness and nature of cover material in Utopia Planitia, Mars: Journal of Geophysical Research–Planets, v. 109, E02006, doi: 10.1029/2003JE002144.

Buczkowski, D.L., and McGill, G.E., 2002, Topography within circular grabens: Implications for polygon origin, Utopia Planitia, Mars: Geophysical Research Letters, v. 29, 1155, doi: 10.1029/2001GL014100.

Burr, D.M., 2011, Sedimentology in a reduced-gravity environment: Submarine analogs for streamlined forms on Mars: Geology, v. 39, p. 703–704, doi: 10.1130/focus072011.1.

Cartwright, J., 2011, Diagenetically induced shear failure of fine-grained sediments and the development of polygonal fault systems: Marine and Petroleum Geology, v. 28, p. 1593–1610.

Cartwright, J.A., and Dewhurst, D.N., 1998, Layer-bound compaction faults in fine-grained sediments: GSA Bulletin, v. 110, p. 1242–1257.

Cartwright, J., James, D., and Bolton, A., 2003, The genesis of polygonal fault systems: A review, *in* van Rensbergen, P., Hillis, R.R., Maltman, A.J., and Morley, C.K., eds., Subsurface Sediment Mobilization: Geological Society of London Special Publication 216, p. 223–243.

Clifford, S.M., and Parker, T.J., 2001, The evolution of the Martian hydrosphere: Implications for the fate of a primordial ocean and the current state of the northern plains: Icarus, v. 154, p. 40–79.

Cooke, M., Islam, F., and McGill, G., 2011, Basement controls on the scale of giant polygons in Utopia Planitia, Mars: Journal of Geophysical Research–Planets, v. 116, E09003, doi: 10.1029/2011JE003812.

Dunlap, D.B., Wood, L.J., Weisenberger, C., and Jabour, H., 2010, Seismic geomorphology of offshore Morocco's east margin, Safi Haute Mer area: AAPG Bulletin, v. 94, p. 936–936.

Goulty, N.R., 2008, Geomechanics of polygonal fault systems: A review: Petroleum Geoscience, v. 14, p. 389–397.

Goulty, N.R., and Swarbrick, R.E., 2005, Development of polygonal fault systems: A test of hypotheses: Journal of the Geological Society, v. 162, p. 587–590, doi: 10.1144/0016-764905-004.

Head, J.W. III, Hiesinger, H., Ivanov, M.A., Kreslavsky, M.A., Pratt, S., and Thomson, B.J., 1999, Possible ancient oceans on Mars: Evidence from Mars Orbiter Laser Altimeter data: Science, v. 286, p. 2134–2137, doi: 10.1126/science.286.5447.2134.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., and Marchant, D.R., 2003, Recent ice ages on Mars: Nature, v. 426, p. 797–802.

Hiesinger, H., and Head, J.W. III, 2000, Characteristics and origin of polygonal terrain in southern Utopia Planitia, Mars: Results from Mars Orbiter Laser Altimeter and Mars Orbiter Camera Data: Journal of Geophysical Research–Planets, v. 105, p. 11,999–12,022, doi: 10.1029/1999JE001193.

Jackson, C.A.L., 2011, Three-dimensional seismic analysis of megaclast deformation within a mass transport deposit; Implications for debris flow kinematics: Geology, v. 39, p. 203–206, doi: 10.1130/G31767.1.

Lane, M.D., and Christensen, P.R., 2000, Convection in a catastrophic flood deposit as the mechanism for the giant polygons on Mars: Journal of Geophysical Research–Planets, v. 105, p. 17,617–17,627, doi: 10.1029/1999JE001197.

Levy, J.S., Head, J.W., Marchant, D.R., and Kowalewski, D.E., 2008, Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution: Geophysical Research Letters, v. 35, L04202, doi: 10.1029/2007GL032813.

Levy, J., Head, J., and Marchant, D., 2009, Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations: Journal of Geophysical Research–Planets, v. 114, E01007, doi: 10.1029/2008JE003273.

Levy, J.S., Marchant, D.R., and Head, J.W., 2010, Thermal contraction crack polygons on Mars: A synthesis from HiRISE, Phoenix, and terrestrial analog studies: Icarus, v. 206, p. 229–252.

Lucchitta, B.K., Ferguson, H.M., and Summers, C., 1986, Sedimentary deposits in the northern lowland plains, Mars: Journal of Geophysical Research–Solid Earth and Planets, v. 91, E166–E174, doi: 10.1029/JB091iB13p0E166.

Macdonald, D.I.M., Moncrieff, A.C.M., and Butterworth, P.J., 1993, Giant slide deposits from a Mesozoic fore-arc basin, Alexander Island, Antarctica: Geology, v. 21, p. 1047–1050.

McEwen, A.S., and 32 others, 2007, A closer look at water-related geologic activity on Mars: Science, v. 317, p. 1706–1709, doi: 10.1126/science.1143987.

McGill, G.E., 1986, The giant polygons of Utopia, northern Martian Plains: Geophysical Research Letters, v. 13, p. 705–708.

McGill, G.E., and Hills, L.S., 1992, Origin of giant Martian polygons: Journal of Geophysical Research–Planets, v. 97, p. 2633–2647.

Mellon, M.T., 1997, Small-scale polygonal features on Mars: Seasonal thermal contraction cracks in permafrost: Journal of Geophysical Research–Planets, v. 102, p. 25,617–25,628.

Moscardelli, L., and Wood, L., 2008, New classification system for mass transport complexes in offshore Trinidad: Basin Research, v. 20, p. 73–98.

Moscardelli, L., and Wood, L., 2011, Deep-water erosional remnants in eastern offshore Trinidad as terrestrial analogs for teardrop-shaped islands on Mars: Implications for outflow channel formation: Geology, v. 39, p. 699–702, doi: 10.1130/G31949.1.

Mouginot, J., Pommerol, A., Beck, P., Kofman, W., and Clifford, S.M., 2012, Dielectric map of the Martian northern hemisphere and the nature of plain filling materials: Geophysical Research Letters, v. 39, L02202, doi: 10.1029/2011GL050286.

Mutch, T.A., Arvidson, R.E., Guinness, E.A., Binder, A.B., and Morris, E.C., 1977, The geology of the *Viking* Lander 2 site: Journal of Geophysical Research, v. 82, p. 4452–4467.

Parker, T.J., Saunders, R.S., and Schneeberger, D.M., 1989, Transitional morphology in west Deuteronilus Mesae, Mars—Implications for modification of the lowland upland boundary: Icarus, v. 82, p. 111–145.

Parker, T.J., Gorsline, D.S., Saunders, R.S., Pieri, D.C., and Schneeberger, D.M., 1993, Coastal geomorphology of the Martian northern plains: Journal of Geophysical Research–Planets, v. 98, p. 11,061–11,078.

Shin, H., Santamarina, C., and Cartwright, J.A., 2008, Contraction driven shear in compacting uncemented sediments: Geology, v. 36, p. 931–934, doi: 10.1130/G24951A.1.

Werner, S.C., Tanaka, K.L., and Skinner, J.A., 2011, Mars: The evolutionary history of the northern lowlands based on crater counting and geologic mapping: Planetary and Space Science, v. 59, p. 1143–1165.

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