Seasonal variations of polygonal thermal contraction crack patterns in a south polar trough, Mars

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[1] We present observations of seasonal variations in polygonal crack patterns located in a polar trough on the south polar cap of Mars; previously, there was no direct observation showing that these patterns change. Polygonal patterns on Mars are attributed to thermal contraction cracking, which is commonly observed in periglacial environments on Earth. In this paper we discuss observations based upon the high-resolution image data of the Mars Orbiter Camera and focus on the reconstruction of the seasonal development. The image-based observations are further supported by temperature data. We show that the south polar trough pattern is located in an active geologic unit, which undergoes seasonal variations and annual crack formation. Furthermore, there are strong indications showing these contraction-crack processes take place in a thin layer that might be composed of water-ice and is located beneath the seasonal carbon dioxide ice cover.


1. Introduction

[2] As part of our mapping and classification work focused on Martian south polar polygonal patterns [van Gasselt et al., 2003, 2004], we have taken special interest in areas that have been imaged two or more times by the Mars Orbiter Camera (MOC) instrument onboard Mars Global Surveyor (MGS) in order to identify seasonal variations and modifications. In this paper we present multitemporal observations of variations in polygonal patterns and a qualitative discussion regarding their formation on the basis of several high-resolution MOC Narrow Angle (MOC-NA) images that cover a south polar trough (SPT) at about 281° eastern longitude and 87° southern latitude (Figure 1). This SPT is incised into the south polar residual cap (SPRC), exposing underlying dark-lane deposits. Our discussion is predominantly based upon image observations at two locations and is further supported by surface temperature data obtained by the Thermal Emission Spectrometer (TES) onboard MGS and the brightness temperature record obtained through the Thermal Emission Imaging Subsystem (THEMIS) onboard Mars Odyssey (MO). As the observed polygonal pattern is situated in a SPT, where desiccation or contraction cracking due to lava cooling do not occur, we will hereafter discuss our observation in the context of thermal contraction cracking of the surface caused by large seasonal temperature gradients.

2. Background

[3] Small-scale polygonal patterns are characteristic landforms familiar to both periglacial and desert environments on Earth. Their formation is attributed either to thermal contraction cracking of the surface layer (frost fissures) or to desiccation of mud sediments, respectively.

[4] After almost 2 decades of terrestrial investigations (Figrin [1823] as cited in the work of Washburn [1979]), theoretical modeling [Leffingwell, 1915; Lachenbruch, 1962] and detailed field work [Black, 1974; MacKay, 1974, 1975, 1986, 1992], the mechanisms involved in thermal contraction cracking processes are reasonably understood although the results of theoretical models often are not supported by evidence from field work [French, 1996; Lachenbruch, 1962; Black, 1976; MacKay, 1992].

[5] In general, polygonal crack patterns occur in terrestrial permafrost when a rapid temperature drop causes a contraction of the permafrost material which is controlled by the coefficient of linear expansion of ice [Leffingwell, 1915; Lachenbruch, 1962; French, 1996].

[6] The initial fissures and cracks might close during spring seasons or, if seasonal thaw water is present, might be filled with water, which freezes during colder periods and produces a vertical ice vein. An initial fissure presents a mechanically weak zone in the strength of permafrost, therefore it is probable that an ice-filled fissure will be reopened during the next freeze cycle and new thaw water will penetrate. After several years of freeze-thaw cycles, a vertical ice wedge might form and can reach a depth of up to several tens of meters and exceed a surface width of 4 m [French, 1996]. In plan view, the fissures propagate over several tens of meters, intersect at characteristic angles and form orthogonal or hexagonal polygonal shapes. In environmental conditions where moisture is not available, sand might instead penetrate into the fissures and produce vertical sand wedges as described by Pewe [1959].
Martian landforms with a striking resemblance to terrestrial periglacial polygonal systems (Figure 2) have been observed and characterized for the first time on the basis of Viking Lander images and high-resolution Viking Orbiter frames [Mutch et al., 1977; Lucchitta, 1981, 1983]. These Martian midlatitude landforms have been interpreted as possible ice-wedge polygons [Mutch et al., 1977; Lucchitta, 1981]. It has to be kept in mind, however, that ice wedges as an expression of vertical and lateral growth of ice-filled contraction fissures require seasonal liquid water. New insights regarding the origin and especially the global distribution of polygonal crack networks have been provided by several authors on the basis of high-resolution data from the MGS MOC-NA instrument [Malin et al., 1992; Malin and Edgett, 2001]. Research concentrates on comparative morphologic and morphometric issues [Yoshikawa, 2000; Seibert and Kargel, 2001; Kuzmin et al., 2002; van Gasselt et al., 2003; Mangold et al., 2004], resurfacing times [Sletten et al., 2003] and the global as well as regional distribution [Kuzmin and Zabalueva, 2003; van Gasselt et al., 2003]. In-depth models on the formation linked to the theory of Lachenbruch [1962] have been provided by Mellon [1997].

While definitive evidence for the method of formation of small-scale polygons is lacking, image interpretation combined with studies on ice stability in the Martian regolith and measurements by the Neutron Spectrometer instrument onboard MO [Mangold et al., 2004] suggest that these landforms are the result of thermal contraction cracking of the upper surface layer. In contrast to the mid- and high-latitude polygonal patterns, the Martian south polar region (Figures 3 and 4) is being currently investigated with the primary focus on the distribution, type classification and correlation with geologic units [van Gasselt et al., 2003]. Only a few results regarding correlation with the distribution...
and influence of subsurface water have been presented [Kossacki and Markiewicz, 2002; Piqueux et al., 2003]. It seems, however, that variations in the structure and dimensions of polygonal landforms are greater in the south polar region when compared to the midlatitude and high-latitude regions.

In contrast to the north polar cap where residual ice consists of water [Kieffer et al., 1976] with small admixtures of dust, the south polar residual ice consists predominantly of carbon dioxide [Kieffer, 1979]. It has been suggested that the south polar cap contains a considerable water reservoir beneath the perennial carbon dioxide cover [Jakosky and

Figure 3. Three overlapping MOC-NA image scenes at location A crossing a south polar trough which is incised into the residual cap at 281.4°E and 87.0°S. (a) MOC-NA M07/02129 was acquired in mid-September 1999 at $L_S = 204.1^\circ$ with a scaled pixel width of 1.38 m. (b) MOC-NA M12/00730 was taken in February 2000 at $L_S = 296.7^\circ$ with a scaled pixel width of 1.38 m. (c) MOC-NA E11/03905 was acquired in late December 2001 at $L_S = 297.6^\circ$ with a scaled pixel width of 1.45 m. Lowercase letters in Figures 3b and 3c refer to image scenes in Figure 11. Also note, that within the “Swiss cheese” terrain slight enlargements of intra-mesa pits can be observed in the summertime image data, as described in detail by, e.g., Thomas et al. [2000], Malin et al. [2001], and Byrne and Ingersoll [2003]. The images have been processed and stereographically projected with a center longitude of 281.4°E and a map scale of 1.70 m per pixel. Sun illumination comes from the west in all three images.
Figure 4. Composition shows MOC-image examples for location B which is located to the southeast of location A. (a) MOC-NA R11/04160 shows a traverse of the same SPT in summer, when seasonal CO$_2$ has sublimated completely. The southeastern rim belongs to the residual polar cap and shows the characteristic “Swiss cheese” terrain. At the transition between rim and trough-center several polygon patterns can be observed which are regenerated each year (Figures 4c–4e). (b) shows the trough-parallel configuration of seasonal CO$_2$ and dark material. Scale bar is 500 m. Image sequence (c) M12/02337, (d) E12/00629, and (e) R11/04160 show repeated MOC images with scenes from the southeastern rim of the trough in Figure 4a. All images were obtained during midsummer ($L_s = 304^\circ - 306^\circ$). In Figures 4c–4e a different polygonal pattern is visible as illustrated by the sketch map below each image. Furthermore, it is noteworthy that the “Swiss cheese” terrain pattern (lower right-hand quadrangle) has been altered.
ideal environment for the formation of contraction crack
(SPLD) underneath the residual ice cap seems to provide an
dermal environment of the south polar layered deposits
cap and in areas adjacent to it. The composition and
amounts of water reside below the residual carbon dioxide

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**3. Data Source and Processing**

**3.1. MOC Image Data**

[11] In order to estimate the accuracy of the data and the
validity of observations, we briefly describe the main
procedures concerning the image data preparation. For
photogeologic interpretation and measurement purposes,
all MOC-NA compressed raw images have been processed
using standard USGS ISIS and JPL VICAR routines. For
location A (Figure 5), the processed image data have a
horizontal resolution between 1.43 m per pixel (M12/00730), 1.84 m per pixel (E11/03905) and 2.18 m per pixel
(M07/02129). In order to achieve maximum accuracy and
comparability, the image data have been (1) prerecified
using the MOLA digital terrain model and (2) projected
stereographically with a map scale of 1.70 m per pixel, a
center longitude of 281.4°E and a center latitude of 90°S.
The accuracy of the MOC-NA camera pointing ensured that
offsets were less than six to seven pixels in each direction.
Artifacts due to different imaging parameters can be ruled
out for following reasons: The local true solar times during
imaging are between 18.13 (M12/00730), 18.32 (E11/03905) and 19.39 decimal hours (M07/02129). This results
in rather high but almost identical incidence angles of 68°
for both M12/00730 and E11/03905 as well as 81° for M07/
02129. MOC-NA images M12/00730 and E11/03905,
which have been prepared for a statistical comparison,
have time offsets of only 0.19 decimal hours and variations in
incidence angles are negligible. The large emission-angle
difference of approximately 18° between M12/00730 and
E11/03905 has no influence on the image geometry after
orthorectification using the digital terrain model. For
mapping purposes and comparability of polygon statistics,
minor corrections using manual tie point selections and
image rectification have been performed. The accuracy of
camera pointing and nearly identical imaging parameters
make the overall image comparability of the images at
location A outstanding (see Table 1).

(Figure 5) range from 1.4 m per pixel (M12/02337) to 2.9 m
per pixel (E12/00629, R11/04160). The center longitude for
all images is 283.3°E. As these scenes were not utilized for
mapping purposes and statistics, no manual rectification
has been applied. The imaging parameters for location B are
equal to location A (see Table 2).

**3.2. THEMIS and TES Data**

onboard MGS have been collected using the provided

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**Table 1. Original MOC-NA Image Characteristics of M07/02129,**
**M12/00730, and E11/03905 at Location A (281.4°E)**

<table>
<thead>
<tr>
<th>MOC-NA</th>
<th>M07/02129</th>
<th>M12/00730</th>
<th>E11/03905</th>
</tr>
</thead>
<tbody>
<tr>
<td>True solar time, decimal hours</td>
<td>19.39</td>
<td>18.13</td>
<td>18.32</td>
</tr>
<tr>
<td>Pixel width, m/pixel</td>
<td>2.18</td>
<td>1.43</td>
<td>1.84</td>
</tr>
<tr>
<td>Solar longitude, °E</td>
<td>204</td>
<td>297</td>
<td>297</td>
</tr>
<tr>
<td>Center longitude, °E</td>
<td>281.4</td>
<td>281.4</td>
<td>281.7</td>
</tr>
<tr>
<td>Incidence angle, °</td>
<td>80.9</td>
<td>67.8</td>
<td>68.1</td>
</tr>
<tr>
<td>Emission angle, °</td>
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<td>0.3</td>
<td>17.9</td>
</tr>
<tr>
<td>North azimuth, °</td>
<td>161</td>
<td>162</td>
<td>164</td>
</tr>
<tr>
<td>Sun azimuth, °</td>
<td>59</td>
<td>68</td>
<td>68</td>
</tr>
</tbody>
</table>

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*The individual scenes cover the southwestern part of the SPT. The summertime images have been analyzed for the characterization of the polygonal pattern.

**Table 2. Original MOC-NA Image Characteristics of M12/02337,**
**E12/00629, and R11/04160 at Location B (283.3°E)**

<table>
<thead>
<tr>
<th>MOC-NA</th>
<th>M12/02337</th>
<th>E12/00629</th>
<th>R11/04160</th>
</tr>
</thead>
<tbody>
<tr>
<td>True solar time, decimal hours</td>
<td>17.68</td>
<td>17.89</td>
<td>18.16</td>
</tr>
<tr>
<td>Pixel width, m/pixel</td>
<td>1.38</td>
<td>2.90</td>
<td>2.90</td>
</tr>
<tr>
<td>Solar longitude, °E</td>
<td>306.5</td>
<td>304.4</td>
<td>306.4</td>
</tr>
<tr>
<td>Center longitude, °E</td>
<td>282.8</td>
<td>283.1</td>
<td>283.7</td>
</tr>
<tr>
<td>Incidence angle, °</td>
<td>69.8</td>
<td>69.4</td>
<td>70.1</td>
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<tr>
<td>Emission angle, °</td>
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<td>17.9</td>
</tr>
<tr>
<td>North azimuth, °</td>
<td>156</td>
<td>159</td>
<td>160</td>
</tr>
<tr>
<td>Sun azimuth, °</td>
<td>59</td>
<td>68</td>
<td>66</td>
</tr>
</tbody>
</table>

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*The individual scenes cover the central part of the SPT.
Vanilla software package. In order to characterize the surface of the polar trough throughout the Martian south polar seasons, we collected data during seasons of MOC image acquisition for location A (i.e., $L_S = 204^\circ \pm 3^\circ$ and $L_S = 297^\circ \pm 3^\circ$). To obtain a representative data set, the data lists have been split into daytime (1000–1600 LT) and nighttime (2000–0600 LT) values (Figure 6). Surface pressure data have been excluded as they showed nearly constant values throughout the seasons and are below 4 mbar, allowing sublimation of CO$_2$ at approximately 140 K.

The ground resolution of the TES data varies with the flight altitude of the MGS spacecraft. The instantaneous field of view (IFOV) is 8.5 mrad [Christensen, 2001], which provides a 2800 to 3000 m pixel resolution for the TES measurements at an altitude of 350 km. In order to account for multiple orbit coverage, data have been median filtered and plotted with the appropriate pixel sizes. For direct comparison with the MOLA topography (IAU2000), TES data (IAU94) have been adjusted to fit the MOLA reference (i.e., planetocentric latitudes, positive easting). As the spatial resolution of the TES data is not high enough to resolve the polar trough in detail, MOLA contour lines have been overlaid in each TES plot. We are aware that a ground surface sampling interval of approximately 3 km, which in fact covers the major parts of the trough, will obscure the data and present only approximated values. Moreover, the data have natural limitations (e.g., noise ratios, calibration errors, atmospheric effects, errors in the low-temperature regime) [Christensen et al., 1992; Christensen, 2001]. Midwinter data are not available due to the mapping characteristics of the TES instrument, while midspring data, taken at $L_S = 225^\circ \pm 3^\circ$ and failing to cover the SPT, have therefore been excluded. Fortunately, several TES measurements cover the SPT very well during relevant dates, making a reconstruction partly possible.

In order to estimate the accuracy of the TES data measurements, we additionally utilized a high-resolution THEMIS brightness temperature record (BTR) and compared the brightness temperature values for both instruments (Figures 7, 6d, 6e, and 6f). Without knowing the surface
emissivity, the brightness temperature of course provides no information about the real surface temperatures. We can clearly see that brightness temperature during $L_s = 313$° drops from >225 K at the center of the trough to about 165 K at its outer rim (Figure 7). This 60 K temperature decrease over a lateral distance of about 3–4 km would be incorporated into a single brightness temperature value within the TES data. As a result, we would expect a true value between these two extremes, depending on where TES took its measurements. Therefore it is reasonable to assume slightly larger values for the trough interior than those acquired by TES.

4. Observations

[16] In this paper we focus on two locations, referred to as location A and location B (Figure 5), in order to provide insight into the seasonal development of the SPT located at about 281.0° E and 87.0° S. Location A has been imaged at least five times between 1999 and 2001. Three images were acquired with a considerable overlap (M07/02129, M12/00730 and E11/03905). MOC-NA image M04/03749 has been excluded from our discussion as it is nearly identical to the M07/02129 scene. Image M09/04839 does not show a significant overlap with the other three images but has been included so that the analysis of seasonal variations can be completed. Location B is located near the center of the SPT and is covered by three MOC scenes (M12/02337, E12/00629 and R11/04160), which were all taken during the summer seasons in 2000, 2002, and 2003. In contrast to the images for location A, these images have a more supplementary character and were processed using standard processing methods. See Figure 8 for a diagram showing the time line of MOC-image acquisition.

4.1. Topographic and Morphologic Settings

[17] The SPT is one of several circumpolar spiraling troughs that cut into the residual polar ice cap, revealing dark-lane material beneath.
[18] The rims of the northeast-southwest trending SPT and their adjacent terrain have a mean topographic elevation of approximately 3200 m in the southeast and 3000 m in the northwest (Figure 5). At its center, the elevation of the trough is approximately 2700 to 2800 m. In the southwest, the trough becomes more narrow and shallow and bends to the southeast, where it terminates as a conical hook-shaped depression. The trough is characterized by several large rim-parallel ridges and furrows, which are irregularly shaped and form a highly undulated terrain surface.
[19] In cross section, the trough is highly asymmetrical (Figure 9) with a southeastern (sunlit) flank that is steeper in its upper part and reaches and elevation of 3170 m (over MOLA reference datum). The lower region of the flank slopes more gently toward the center of the trough, which is located at an elevation of approximately 2820 m. The

Figure 7. Brightness temperature (BTR) of the SPT discussed in the text on the basis of the THEMIS image I08814007BTR located at -87.0° N and 253.9° E. Solar longitude during imaging of the THEMIS instrument is slightly later ($L_s = 313$°) than our observations in the MOC-NA summer image data ($L_s = 297$°). No IAU conversion during processing has been applied as the characteristic hook-shaped southeastern trough can be localized visually well enough.

Figure 8. Years and Seasons of image acquisition of the MOC images discussed in the text. MOC-image numbers located on the same level show repeated imaging of an area.
overall slope angle is approximately 4° to 5°. The northwestern flank slopes gently (about 3°) to an elevation of approximately 3000 m.

[20] In the image data for location A (Figure 3), the SPT has a maximum width of about 7 km and is framed by a smooth, relatively dark deposit on the northwestern trough shoulder and a well-defined so-called “Swiss cheese” pattern on the southeastern flank. The darker deposit on the northwestern flank extends to the border of the MOC-NA image M07/02129 and is dissected by typical CO2 related collapse and sublimation features, similar to the features observed on the southeastern flank.

4.2. Seasonal Observations

[21] The MOC-NA scenes for location A were taken during early southern summer at $L_S = 297°$ (M12/00730 and E11/03905) and around midsummer at $L_S = 204°$ (M07/02129). MOC-NA scene M04/03749 covers the location a bit earlier at $L_S = 195°$, but no substantial difference to the M07/02129 scene has been found (Figure 8). Additionally, three images (M12/02337, E12/00629 and R11/04160) for the midsummer season at $L_S \approx 305°$ have been taken a few kilometers to the northeast at location B (Figure 5). We will discuss our seasonal observations with the help of these sets of images starting at early spring (Figure 8).

[22] On the basis of springtime observations at $L_S = 204°$ (Figure 3a) as well as TES derived temperature data of that time, the sublimation temperature of CO2 has been reached and the seasonal ice cap (Figures 6a, 6d) is receding but has not yet reached its minimum extent. The polar-trough infill is characterized by CO2-ice deposits with an overall rough surface texture that appears to be draped over the rough and undulating topography. As the topography of the trough interior is still clearly visible, we can assume that the deposit is quite thin and homogeneously spread over the surface. The transition from the southeastern “Swiss cheese” terrain toward the southeastern wall of the trough is clearly defined by an abrupt termination of the characteristic sublimation pattern and a sudden increase in brightness, due to the illumination conditions. The transition from the trough center to the southeast-facing wall is characterized by an abrupt decrease in relative brightness caused by the low sun elevation (incidence angle of 81°). The northwestern wall presents a distinct pattern of elongated grooves parallel to the main trough axis (Figure 3a). This pattern disappears gradually towards the upper part of the wall.

[23] In the MOC scene M09/04839 which was taken in late spring at $L_S = 246°$ (Figure 10), a very faint polygon pattern seems to shine through a thin CO2 cover. Obviously, the CO2 cover started to sublimate substantially between $L_S = 204°$ and $L_S = 246°$ which caused thinning of the CO2 surface layer. This observation is in general accordance with the springtime and summertime TES derived temperature increases of up to 10 K (Figures 6a–6c).

[24] In the early summer image data M12/00730 and E11/03905 ($L_S \approx 297°$ of 2000 and 2001) of location A (Figures 3b and 3c), several dark polygonal shapes that are covered by a thin veneer of CO2-ice or snow become faintly visible. At the southeastern wall of the SPT, these polygons are very well defined in both summertime images. The southeastern rim of the polar trough is somewhat irregular, but still distinct in both images due to a decrease in relative brightness. The polygonal pattern, however, has changed significantly in both images (Figures 3b, 3c, and 11b–11d). Toward the trough’s center, irregular elongated patches of the underlying dark material become visible. The center is almost completely free of seasonal CO2 and large areas of the dark material are visible. Toward the northwest, the frost cover once again becomes more dense while polygonal patterns reappear and gradually vanish under the smooth CO2 cover at the northern wall.

[25] It is noteworthy that the northwestern wall of the SPT shows several fissures and furrows parallel to the main polar trough (Figure 11a). These features have also been observed in the springtime image and form a somewhat elongated trough-parallel pattern of rills and furrows. Since the appearance of these trough-parallel patterns is completely different from the center-trough polygons, we can assume that there is no genetic connection between these types. The distribution and geometry of these furrows,
however, are exactly the same in all three images, giving an additional guarantee that the differences of polygonal patterns in the trough’s center are not caused by obscured imaging characteristics. We assume that these northwestern-wall furrows could be attributed to a very slow slope movement or that they are a surface expression of subsurface compaction of the CO₂ cover.

In midsummer at $L_S = 306^\circ$ the trough in location B is completely free of seasonal CO₂ cover (Figure 4a) and, except for very few areas at the rim of the trough where the seasonal cracked surface layer is present (Figures 4c, 4d, and 4e), no polygonal pattern can be observed. The sequence in Figures 4c–4e shows the region on the southeastern flank over 3 years.

### 4.3. Characterization of Polygonal Pattern

On a regional (kilometer) scale, the observed polygonal patterns are equally distributed in both summertime images at locations A and B (Figures 3b, 3c, 12a, and 12b). They can be observed across the SPT surface where at least a thin cover of CO₂ still blankets the dark-lane material. On a local (meter) scale, however, the fissure network, although showing identical shape characteristics, differs considerably in terms of the location of individual fissures (Figures 4c–4e and 11b–11d).

The diameters of the individual polygons range from ≤10 to about 140 m with a distinct average at diameters between 50 and 60 m (12% of all diameters measured) (Figure 12e). The slight shift in the distribution toward larger values is probably caused by a deficit in detected polygons in the small-diameter range due to limitations in image resolution. The frequency distributions for the diameters in both summertime images of location A are nearly identical. The size distribution fits well into the overall size distribution measured at the south polar area [van Gasselt et al., 2003] and compares closely to that described by Lučchitta [1983], Seibert and Kargel [2001] who find similar diameter ranges between 10 and 250 m with an average diameter of approximately 50 m, and to that described by Kuzmin and Zabalueva [2003] in their analyses of 400 midlatitude MOC-NA images. However, the mean diameter size is somewhat larger than described by Paepe et al. [2001] for orthogonal networks in midlatitudes (30 m) and by Yoshikawa [2000] (20 m), who compared a few midlatitude polygonal crack patterns with terrestrial Arctic and Antarctic polygons. Even more importantly, the values are comparable to those measured in terrestrial environments as described by, e.g., Lachenbruch [1962], Yershov [2004], and Washburn [1979], suggesting similar cracking conditions.

The frequency distribution of conjunction types and conjunction angles (Figures 12c and 12d) are descriptive parameters that allow insight into the formation of polygonal crack patterns. In a simplified view, the intersection angle at a three-ray conjunction, i.e., a conjunction between at least two polygonal troughs is generally $120^\circ$, forming a pattern of hexagonal polygon shapes. A four-ray conjunction is most likely formed when two individual polygonal fissures intersect orthogonally. A group of orthogonally intersecting polygonal fissures forms a surface characterized by an orthogonal pattern. Our data show an almost identical relative frequency of three-ray conjunctions (65–70%) and four-ray (30–35%) conjunctions in both images (Figure 12d).

The conjunction angles between individual polygonal troughs range from $80^\circ$ to $140^\circ$ in both summertime images with two distinct maxima at $90^\circ$ to $100^\circ$ (orthogonal conjunction) and at about $120^\circ$ (hexagonal conjunction) (Figure 12c). In the M12/00730 image measurements, the $90^\circ$ maximum is more distinct and contains approximately 75% of all observed conjunctions. The values for the measurements in the E11/03905 image show a distinct bimodal distribution, again with an absolute maximum at orthogonal conjunctions. It has to be kept in mind that not all polygon fissures might have been accounted for in the statistics, due to the CO₂ cover at the polar trough boundaries and the large areas with outcrops of dark material.

The majority of polygonal troughs observed in the MOC images are slightly arcuate and extend over distances of a few hundred meters to several kilometers. A width range of 2–3 m for individual polygon cracks was determined by measuring the width of the dark crack infill. This value might be far too large and may be caused by the image resolution limits and the diffuse distribution of dark material. The dark infill seems to be of the same composition as the dark outcrops. This suggests the polygon fissures are a trap for this material, which might be transported by seasonal polar eolian processes. This material may originate from dust that was originally incorporated into the seasonal CO₂ cover and was subsequently deposited after the CO₂ sublimated.

Despite limits of image resolution, it is clear that the polygonal fissures are not characterized by a significant central depression or upturned edges. The polygons delineated by the fissures are neither low- nor high-center
polygons and the polygonal shapes appear absolutely flat (Figures 11b–11d).

5. Discussion and Implications

[33] The SPT development, as observed in the MOC images and TES data, is characterized by (1) a homogeneous coverage of CO$_2$ in the SPT up to at least early spring ($L_S = 204^\circ$) with no visible polygonal crack pattern on the surface; (2) a continuous but thin coverage of CO$_2$ during midspring ($L_S = 245^\circ$) where a polygonal pattern becomes faintly visible underneath the remaining CO$_2$ cover; (3) a well-defined polygonal crack pattern between midspring and early summer ($L_S = 297^\circ$) when substantial amounts

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**Figure 11.** Comparison of high-resolution scenes taken from summertime MOC-NA images M12/00730 and E11/03905. Lowercase letters in the scenes refer to locations marked in Figure 3. (a) Trough-parallel lineations on northwestern wall which can be observed in the spring-as well as in the summertime images, image width is 6 km. (b) Northwestern part of trough, remnants of seasonal CO$_2$ ice cover the lower-elevation areas. Higher elevated areas are defined by characteristic dark outcrops of the trough infill underneath. Oriented orthogonal polygon pattern occur at the southern outcrop. Image width is 4 km. (c) Highly modified polygonal pattern at the trough center, image width is 3.1 km. (d) Southeastern rim near the transition to a thick CO$_2$ layer. The dark patches have a fine-scaled checkerboard texture. Image width is 4.4 km. North direction is always up.
Figure 12. Sketch maps of surface features and polygonal crack patterns in MOC-NA M12/00730 (a) and E11/03905 (b) scenes of location A. North is up. Below: Polygon statistics for conjunction angles (c), conjunction types (d), and diameters (e).
of seasonal CO₂ have almost completely sublimated and the remaining CO₂ coverage is distributed in a patchy way; (4) a central SPT unit that is completely free of CO₂-ice by midsummer (L₆ = 306°).

[34] The observation that the polygonal shapes are covered during spring and become visible in summer suggests that the sequence of layers in the SPT is characterized by at least three units. The top layer is a seasonal CO₂-ice or snow layer that is present in the spring, but also appears to exist in the fall and winter. The middle unit, hereby referred to as the “cracked surface layer” or intermediate unit, becomes exposed at the latest by early summer and vanishes by midsummer. Within this layer polygonal fractures are visible. The bottom unit consists of dark material of the trough deposits (dark trough unit).

[35] The polygonal shapes are relatively smooth and characteristics, such as upturned trough edges and central troughs, are missing. Although the mechanism of upturning of the surface layer over an ice wedge remains debated [e.g., MacKay, 1980], one common argument is that upturned rims over a fissure can be connected with the growth of ice or sand wedges and upturning occurs as a result of reexpansion during several freeze-thaw cycles [Lachenbruch, 1962]. The smooth nature of the polygons, coupled with the observation that the polygonal crack patterns disappear during midsummer, suggest ice wedges are not formed and these cracks are (1) seasonal and (2) are recurring surface expressions of thermal contraction processes.

[36] The types of intersections, i.e., orthogonal or hexagonal, have been discussed by various authors. Orthogonal polygon networks are most likely formed in inhomogeneous materials [Lachenbruch, 1962; French, 1996] and attributed to differences in horizontal stress, caused by horizontal temperature variations [Lachenbruch, 1962]. This type of polygon pattern occurs where earlier cracks, which tend to follow random sinuous courses, are intersected by later fractures [Lachenbruch, 1962; French, 1996]. This suggests that the long sinuous cracks predate the perpendicular and the fractures that make up the orthogonal polygons are caused by a single cracking event. Another explanation for the irregular orthogonal pattern might be the degree of development as discussed by Lachenbruch [1966] and Sletten et al. [2003]. In their work, irregular orthogonal systems are an expression of an initial cracking phase. During further development, patterned ground matures and the polygons become smaller and more regular.

[37] Several fracture systems seem to be oriented orthogonally at the SPT (Figure 11b). As this orientation of orthogonal fissures occurs in the vicinity of outcrops of dark sediment, it seems likely that this underlying dark material has a major influence on the horizontal temperature gradient and therefore causes a concentric fracture pattern around these dark material patches. Subsequently, fractures form at right angles to the concentric fractures, resulting in a characteristic pattern of concentric and radial fractures. Along with differences in the thermal property of materials, the mineralogic composition of a material can also affect the orientation in orthogonal systems [Black, 1974]. As the material composition [Lachenbruch, 1962] and the temperature fluctuations [Dostovalov and Popov, 1966] are not precisely known, only a qualitative discussion of polygon sizes is possible here. Nonetheless, the observations are qualitatively consistent with theoretically derived predictions for crack formation.

[38] In order to estimate whether the composition of the cracked surface is remnant CO₂ or more likely a water (or CO₂) dust material that is distinct from the uppermost CO₂ layer, we applied a technique, devised by MacKay [1986] at Illisarvik, to determine the linear expansion coefficient. MacKay [1986] made use of theoretic models by, e.g., Lachenbruch [1962] to estimate the coefficient of linear expansion α [1/C] which controls cracking of surface material. To estimate the “apparent” coefficient of linear expansion α, the crack width (ΔL), the distance between two parallel cracks on the surface L and the mean ground temperature (T) have been used:

\[ \alpha = \frac{\sum \Delta L}{L \cdot \Delta T} \]  

where ΔT is the temperature change relative to 273 K [MacKay, 1986].

[39] In order to estimate α, we have to consider that an individual fissure width can only be approximated. Owing to the limits of image resolution, the 1–2 m widths must be viewed as an absolute maximum and are most likely overestimates. Surface temperatures for the time period of cracking (i.e., winter) are not provided by TES. While 150 K might be a bit warmer than the mean winter temperature at the location of study, this value was used to compare it with the fit provided by Mellon [1997]. We measured across three parallel fissures at two locations: Location 1: L = 125 m, \( \sum \Delta L = 3 \text{ m to 6 m, } \Delta T = 150 \text{ K} \), and Location 2: L = 180 m, \( \sum \Delta L = 3 \text{ m to 6 m, } \Delta T = 150 \text{ K} \).

[40] We obtained rough estimates for α that range from 160 \( \text{·} \) 10⁻⁶/K to 320 \( \text{·} \) 10⁻⁶/K for location 1 and 110 \( \text{·} \) 10⁻⁶/K to 220 \( \text{·} \) 10⁻⁶/K for location 2.

[41] The coefficient of linear expansion for water-ice has been measured to range from 45–50 \( \text{·} \) 10⁻⁶°C for temperatures between 0°C to −40°C; this range applies to terrestrial thermal contraction cracking [MacKay, 1986; Lachenbruch, 1962]. French [1996] provides the slightly lower value of 17 \( \text{·} \) 10⁻⁶°C. On Mars, a fit function of 2.47 \( \text{·} \) 10⁻⁶°C T − 1.17 \( \text{·} \) 10⁻⁵ K, which is valid in a temperature range from below 150 K to 273 K, has been derived by Mellon [1997]. These estimates are all based on experiments by Hobbs [1974]. Although our values are one order larger than those provided by Mellon [1997] for Martian conditions at these temperatures, they remain in the range of laboratory experiments for water-ice (α = 350 \( \text{·} \) 10⁻⁶°C) and measurements at Illisarvik (α = 50–400 \( \text{·} \) 10⁻⁶°C), as described by MacKay [1986]. However, in the case of water ice with considerable admixtures of dust or fine grained material the linear expansion would be significantly lower [Mellon, 1997].

[42] These estimates and the fact that thermal contraction fissures occur in a thin layer only, suggest that the intermediate cracked surface unit may consist of water-ice that is seasonally overlain by CO₂ ice.

[43] The thickness of the cracked layer can not be determined from image observations. However, we suggest that the cracked surface layer is probably thinner than the overlying CO₂ ice cover, which is known to be in range of a few centimeters to decimeters [Smith et al., 2001]...
Aharonson et al., 2003]. This assumption is based upon the observation that the cracked surface is exposed in early summer and completely removed by midsummer, whereas the removal of centimeters to decimeters of more volatile CO₂ takes from early spring to midsummer.

6. Model for Polygon Formation

While the structure of both Martian polygons and their terrestrial counterparts are similar, the time frame for formation and the structure of individual surface units are different. On the basis of our observations and discussions, we create a model to reconstruct the seasonal development of polygonal cracks (Figure 13).

In early summer (location A: M12/00730 and E11/03905 at \(L_S = 297^\circ\)), seasonal CO₂ blankets the polar trough rims. Most of the CO₂ inside the SPT sublimated, revealing a thin veneer of what is probably less volatile H₂O ice. This veneer shows a characteristic polygonal crack network. Where the cracked surface layer has been removed through sublimation the dark underlying trough infill can be observed (Figures 13a–13b).

In midsummer (location B: M12/02337, E12/00629, and R11/04160 at \(L_S = 306^\circ\)), the central SPT surface is free of the cracked surface layer and only the dark trough infill is exposed (Figure 13c). Large temperature values derived from the TES data support this observation.

Presumably during early fall, first a thin layer of H₂O then CO₂ is deposited on the trough surface (Figures 13d–13e). If temperature gradients are large enough, the first thermal contraction cracks could then form in late fall. If the overlying CO₂-layer insulates the H₂O-layer, thermal contraction cracking might occur even during early spring, as observed on Earth [Lachenbruch, 1962]. In this case, CO₂ insulates underlying layers in a similar fashion as the so-called “active layer” on Earth (Figure 13g).

In early spring of the following year (location A: M04/03749 at \(L_S = 195^\circ\) and M07/02129 at \(L_S = 204^\circ\)), the trough is covered by a thick veneer of CO₂ frost. No characteristic polygon patterns can be detected.

During mid spring (location A: M09/04839 at \(L_S = 246^\circ\)), CO₂ is sublimating and a diffuse polygonal pattern can be seen through the CO₂ cover. If the insulating effect of the CO₂ diminishes, thermal gradients might become large enough to cause thermal stresses that exceed the strength of the surface material. The dust, which is incorporated into the sublimating CO₂ layer, is now redistributed on the H₂O layer and fills the polygonal troughs the following summer (Figure 13h).
7. Conclusions

[51] The discovery and reconstruction of active surface cracking at the south pole yield several important conclusions:

[52] 1. On the basis of 3 years of observation in high-resolution MOC image data, polygonal patterns change annually in regions where conditions are favorable, i.e., temperature gradients cause cracking of an intermediate layer which sublimes and deposits annually. So far, we have not found any evidence for changing crack patterns in other locations than the SPT discussed herein.

[53] 2. We see that geologic processes are very active on Mars, which shows that the south polar cap (and its neighboring units) must be considered as an individual geologically active unit [Thomas et al., 2000].

[54] 3. We found strong indications that a layer of H₂O underlies the seasonal CO₂ frost cover. This layer cracks due to thermal contraction and sublimes during summer. This intermediate layer plays a significant role in the development (i.e., shape and size) of thermal contraction cracks.

[55] 4. The shape and scale of polygonal networks in the south polar trough compares closely to terrestrial permafrost polygons.

[56] 5. The shape and scale of polygonal patterns are influenced by the compositional and thermal properties of the dark trough infill. Randomly and orthogonally oriented patterns on Mars are similar to those observed in terrestrial environments; presumably, similar parameters influence the patterns in both environments.

[57] 6. At this SPT, ice wedging can be ruled out, since (1) the cracked intermediate layer is not stable throughout a Martian year and (2) characteristic upturned edges at fissures are missing.

[58] 7. Each year, dark sedimentary material in the SPT accumulates after the cracked surface layer disappears and the fissure infill remains. The amount of sediment that accumulates each year is unknown.

[59] 8. In this context, climatic change plays no role in the evolution of polygonal cracks, since this process is repeated every year and subject to the annual global CO₂/H₂O cycle.

[60] 9. The appearance of the polygonal pattern (shape, size and morphology) could be used to identify similar terrain on Mars in order to locate possible sub-CO₂ water ice and distinguish units of ice wedging and fissuring.

[61] However, the thermal environment and mechanical properties of the surface material were not incorporated into this model of the cracking process. This task will be handed over to those with expertise in this field. In order to fully understand these processes in the south polar region, this type of research must be undertaken. Greater knowledge of these directly observable processes will aid in understanding the behavior and development of thermal contraction cracking as well as possible subsequent wedging in midlatitudes.

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