Characterization and formation of polygonal fractures on Venus

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[1] Fracture theory predicts that polygonal cracks will form in the presence of an isotropic, extensional stress field. On Venus, polygonal fractures are observed on scales several orders of magnitude larger than on Earth, with an average diameter of 1.8 ± 0.9 km. Proposed formation mechanisms include cooling following lava flow emplacement, lithospheric heating, and climate change. Here we examine the characteristics and geologic setting of 204 regions of polygons. Some regions display two spatially overlapping size ranges, with the larger spacing typically 10–25 km. Most polygonal fractures appear to be extensional, but some have the morphology of compressional ridges. Polygons are confined to plains regions and occur in association with shield fields (49%), coronae and coronae-like features (21.3%), tessera (17.5%), and wrinkle ridges (20%). In locations where polygons occur with shield fields, coronae, or both, they appear to have formed contemporaneously. Formation in conjunction with local heating events is consistent with the lithospheric cooling hypothesis. However, there is almost never the predicted decrease in size away from the center of coronae or shield fields. Only a small percentage of coronae and shield fields contain polygons, indicating that they are not typical of the formation process. The climate change-induced scenario is consistent with many characteristics of the polygons, including the small and large size ranges, the compressional ridges, and their occurrence with and without evidence of local heating. Although polygons may have diverse origins, including formation by multiple deformation events, overall polygon characteristics support the climate change hypothesis.

INDEX TERMS: 8010 Structural Geology: Fractures and faults; 6295 Planetology: Solar System Objects: Venus; 8450 Volcanology: Planetary volcanism (5480); 1610 Global Change: Atmosphere (0315, 0325); 5480 Planetology: Solid Surface Planets: Volcanism (8450); KEYWORDS: Venus, thermal stresses, polygons, extensional fractures, climate change


1. Introduction

[2] Polygonal cracks with spacings of 1-100s cm are commonly found on the surface of slowly cooled terrestrial lava flows [e.g., Ryan and Sammis, 1981; Grossenbacher and McDuffie, 1995; Lore et al., 2000]. A uniform tensile stress results from contraction of the melt as it cools, producing hexagonal or nearly hexagonal cracks. In lava lake settings, the polygon diameters can be meters in scale, although these scales may be influenced by deflation stresses [Peck and Minakami, 1968]. On Venus, polygonal features on a much larger scale are observed in Magellan radar images. Initial observations of these features indicated a typical polygon diameter of 1–2 km [Johnson and Sandwell, 1992; Anderson and Smrekar, 1999], several orders of magnitude larger than cooling features with similar shapes on Earth.

[3] Johnson and Sandwell [1992] examined models of both cooling lava flows and of subsurface heating to form the Venusian polygons. They conclude that the cooling lava flow mechanism is unlikely because of the requirement that the flows be at least 20 km thick to generate such large patterns. The subsurface heating model requires a 3°K/km increase in the thermal gradient to cause polygons of the scale observed on Venus [Johnson and Sandwell, 1992].

[4] Recent work on possible climatic variations on Venus suggests an alternative heat source. Models of the response of the atmosphere and surface to volatile outgassing show that very large surface temperature variations are possible [Bullock and Grinspoon, 1996, 2001]. The water and sulfur dioxide estimated to be released by resurfacing events producing global lava thicknesses of 1–10 km lead to surface temperature variations of 90–200°K [Bullock and Grinspoon, 2001]. The surface initially cools in response to the increased cloud cover produced by the volatile release. Over time, the water and sulfur dioxide dissipate due to exospheric escape of H and reactions with surface minerals. The associated reduction in cloud cover causes the surface to heat up slowly. Associated changes in the atmospheric albedo and opacity eventually result in very gradual cooling.

[5] Anderson and Smrekar [1999] developed a model of polygon formation caused by climate change-induced sur-
face temperature variations. This model propagates surface temperature variations predicted by Bullock and Grinspoon [1996, 2001] into the subsurface and calculates the associated thermal stresses, strains, and fracture depths. The formation of polygons with diameters of approximately 2 km is most consistent with the surface cooling predicted for the equivalent of a 1 km thick global lava depth [Anderson and Smrekar, 1999]. The cooling precipitated by such a global resurfacing event would be expected to produce polygons with a relatively uniform size. This model also predicts two scales of deformation due to shallow brittle failure and deeper ductile deformation. Surface heating in response to climate change has been proposed as a formation mechanism for low strain compressional ridges [Anderson and Smrekar, 1999; Solomon et al., 1999]. Solomon et al. [1999] propose that many of the wrinkle ridges on Venus form through this mechanism. In this study we find a number of sites where apparently compressional ridges either occur along with polygons or actually comprise the polygons themselves.

2. Method of Polygon Identification

The global distribution of polygonal fracture patterns on Venus is determined using an automated algorithm to locate candidate regions (P. Moreels and S. E. Smrekar, Watershed identification of polygonal patterns in noisy SAR images, submitted to IEEE Transactions on Image Processing, 2002) (hereinafter referred to as Moreels and Smrekar, submitted manuscript, 2002). This is the first systematic examination of polygonal features using the recently released Fmaps (full resolution radar images). These FMaps have a resolution of 75 m/pixel and cover 96% of the planet. Regions that are visually confirmed to be consistent with polygonal fracture patterns are then characterized with respect to their size, areal extent, fracture orientation, fracture type, stratigraphic position and association with other geologic features. Many new regions are identified, bringing the total number of identified polygon locations to 204, an order of magnitude increase over past estimates. A database of the features identified in the study is given in Table 1, which is available as electronic supporting material.

Polygon locations in the Magellan database are determined using an image processing program based on mathematical morphology. Our method detects the bright edges present in the image and analyzes them to decide if they form polygonal patterns (Moreels and Smrekar, submitted manuscript, 2002). One of the main concerns for analysis of Magellan images is the nature of noise inherent to SAR imaging. Radar noise, known as speckle, is highly correlated and yields poor signal-to-noise ratio. The speckle is usually modeled as a multiplicative random noise. For this reason classical edge detectors, based on the gradient and higher order derivatives of the gray level, cannot be used. Relevant signal variations in dark areas are overlooked, whereas other signal variations due to noise are interpreted as edges in bright areas.

A preprocessing step filters the image to reduce the influence of speckle. We use Lower-Upper-Middle (LUM) filters [Hardie and Boncelet, 1993], which have an advantage over linear filters as they are relatively insensitive to random spikes in the signal. LUM filters have the same smoothing properties as median filters, and their parameters can also be set to have simultaneously signal-sharpening properties.

In a second step, edges are extracted using the “watershed” method. This algorithm works as an analogy to a flooding process. A simulated landscape is generated from the initial image, where the high altitude points would correspond to the bright pixels in the initial image and the low altitude is indicated by dark pixels. Edges are detected through a flooding process in this simulated image. Virtual water (a horizontal datum) is raised evenly throughout the image from the local minima, as if the area were flooding. The last features to be flooded are the crests of the simulated landscape, which represent edges in the initial radar image. This process provides closed, one pixel wide contours.

In order to reduce oversegmentation inherent to the basic watershed method, we introduce a measure of the dynamic of the obtained contours (Moreels and Smrekar, submitted manuscript, 2002). This dynamic characterizes the sallency of detected edges when compared to the rest of the image. The obtained contours are then vectorized, and each identified closed region in the image is characterized by the set of its adjacent edges.

The decision process that accepts or rejects an image as containing polygons is the last step. Several parameters are calculated for each image: average and standard deviation of the dimensions of the patterns, number of edges, orientation. A “cost function” is calculated from those parameters, increasing when the parameters are far from typical values obtained from previously identified locations. The area is accepted as containing polygons if the final “cost” value lies below a previously defined threshold, and rejected otherwise.

Using this method, our code selected about 1900 locations, out of 115,000 Fmap frames. In order not to overlook polygon locations, the final “cost” threshold was set quite high. As a result many irrelevant locations were automatically selected. After visual examination, 204 locations were classified as containing polygons. As discussed below, areas where patches of polygons with similar characteristics occur in close proximity to each other are counted as one location. This number is a lower bound, as there are conditions that would cause the algorithm to overlook polygons, such as if the polygons are extremely faint.

3. Polygon Characteristics

3.1. Introduction

The geologic characteristics of fractures identified in radar images are not always unambiguous. Two-dimensional characteristics such as polygon diameters or orientation (if any) are measured with reasonable precision, but whether or not to count individual patches of polygons as one area or multiple areas requires a judgment. In several
cases we report a single region where others have listed several polygon locations. Whether or not polygons cross flow boundaries, or whether the polygons are comprised of ridges or troughs generally requires interpretation based on two-dimensional analysis in the absence of high-resolution topographic data. As discussed in the next section, their relationship to other geologic features, including relative age, is clear in some locations, but equivocal in others. Thus the results presented here do not agree in every case with past work. However, the large number of regions examined and the fact that most interpretations are relatively straightforward indicate the characteristics presented below are representative of polygons on Venus.

3.2. Polygon Sizes

Polygons range in size from 15 km down to the SAR image resolution (75m/pixel). We define their size as the maximum distance between two vertices. Since most features are nearly equant, this value is typically close to the average diameter. Some images display a gradation in size, down to the resolution, which suggests the existence of patterns with diameter smaller than 75 m. We find an average diameter of 1.8 km for the features. The variance is 0.9 km, which implies that the value of 1.8 km is a good estimation for the size of typical observed polygonal features. This value is in agreement with previously reported results [Johnson and Sandwell, 1992; Anderson and Smrekar, 1999].

Large, regular polygons can be found in only a few locations. We found 7 images containing limited areas of polygons with diameters greater than 8 km (Fmaps 07N043, 33S225, 35S229, 35S253, 42N023, 50S278, 60N135). Of those, the area southeast of Nightingale corona, reported and discussed by Johnson and Sandwell [1992, Figure 2-3] has the largest features with diameters up to 27 km. These are the only polygons observed to date that have a diameter in excess of 15 km. One example of the gradation in size from large to small polygons is shown in Figure 1.

Small polygons with sizes ranging down to the resolution of Magellan’s imaging system are found more commonly (45 locations). Small polygons occur either in association with medium sized ones or form regions with uniformly small diameters, as in Fmap 22S318 (Figure 2). In a number of locations, small diameter polygons occur within more widely spaced fractures. When calculating the average polygon diameter for an entire polygon population, only the small diameters have been included. In most cases the wide fractures have a preferred orientation, such as the radial cracks associated with coronae, or the wider, brighter fractures in Figure 3. Sometimes a large fracture set forms closed patterns that can be considered a second, larger scale set of polygons (Figure 4). Where two scales of polygons

Figure 1. Polygons in Fmap 35S253 that display a gradation in size, from 6 km near the top to 1 km near the bottom. The size of the image is 96 × 82 km.
overlap, the spacing between large fractures varies between 8 and 30 km, with most in the range of 10–25 km. The size of small polygons is the same as in locations where no larger fractures are present. The distribution of the two sizes is shown in Figure 5.

### 3.3. Areal Extent of Polygon Fields

[17] The areal extent of polygon fields is highly variable, ranging from as small as 30 km on a side to as large as 600 km. As the regions are usually unevenly shaped, we simply estimated the east–west and north-south dimensions of each site. Figure 6 is a location map of confirmed polygons, with symbols indicating the areal extent and the average diameter of the polygons within an area. The average diameter of the polygon regions is 216 km.

[18] Some locations display islands of polygons over a large area. In Fmap 56N154 several small polygon fields, each one covering approximately 35 × 35 km, spread over a larger (200 × 200 km) area. Another location with the same configuration is Fmap 48n190. In this case the dimensions of the polygons are relatively constant in all of the small islands (1–2 km in diameter). When several small polygon fields are very close to each other, they are combined and counted as one in our database and indicated as one region in Figure 6. Where appropriate, the diameter of the measured area encompasses all the subregions. The total area of all regions is $8.5 \times 10^6$ km$^2$, or ~2% of the surface of Venus.

### 3.4. Orientation and Number of Sides

[19] Typical polygons have no preferred orientation. We perform an automated analysis of the number of edges per pattern. When edges are short (less than 5 pixels), which is the case in most regions, a polygon edge is simply the line joining two adjacent vertices. If the detected curve between vertices is longer and has a high overall curvature, segments joining vertices are broken further into smaller edges. We calculate an average of six edges per polygon using this approach. This result would correspond to a hexagonal tiling pattern of the plane, each vertex being the intersection point of three edges. A visual examination of the polygon locations shows that most intersections are 3-edge intersections, as noted by Johnson and Sandwell [1992, Figure 4]. This is consistent with the hexagonal shape predicted by theory and commonly seen in columnar joints in lava flows. Aydin and DeGraff [1988] noted that

![Figure 2.](image)

This section of Fmap 22S318 shows a region with small diameter polygons (less than 1 km) that grade down to the resolution of the data. The size of the area is 90 × 112 km.
hexagonal patterns in terrestrial lava flows are commonly seen in the interior of flows, where the stress is isotropic. At the margins, where there is anisotropy, polygons are commonly tetrahedral. Given the large areal extent of polygons on Venus, it is not surprising that they are dominated by the pattern believed to form under isotropic conditions.

[20] When polygons are associated with large fractures, they can exhibit similar fabric or orientation as the fracture zone. In Figure 3 (Fmap 19N071) polygons are interspersed with a locally dominant southwest-northeast oriented fracture belt. In this area, the ratio between length and width is approximately 2.2–2.3 for the small, oriented polygons and has the same value for the wider fractures forming larger polygons.

3.5. Ridges and Troughs

[21] Rough, radar-bright polygon edges in this data set are generally only one or two pixels wide, making it difficult to know whether they are positive topography.
(ridges) or negative topography (troughs). Magellan’s low-resolution altimetry data (5–8 km/pixel [Rappaport and Plaut, 1994]) are not of value at the scale of features in this study. As Johnson and Sandwell [1992] report, some larger fractures can be clearly identified as extensional graben, with steep bounding scarps and a down-dropped, relatively flat floor. In a very few areas it is possible to identify radar “shadows” either for high positive topographic ridges, generally attributable to compressive stresses, or for negative troughs attributable to extensional strain. For several reasons, this analysis can be reliably performed only in a limited number of cases. First, the fractures analyzed in this study typically cover only a few pixels. Second, since the Magellan radar is either “left-looking” or “right-looking”, only the fractures that are North-South oriented can exhibit identifiable radar shadows. Third, frequently the radar-dark side cannot easily be distinguished from the background or from noise.

The absence of unambiguous topographic information forces reliance on two-dimensional morphologic criteria to assess whether a polygonal feature is likely formed in response to compression or extension. In general, the two-dimensional morphology of extensional fractures includes very straight fractures, such as those characteristic of the gridded terrains [Banerdt and Sammis, 1992]. Examples of long, straight fractures similar to those seen in gridded terrains occur in Figure 7. Another indication that some of the polygons form in an extensional stress regime is that the patterns of fracture intersections are similar to those found in columnar joints [Aydin and DeGraff, 1988; Johnson and Sandwell, 1992]. These joints are characteristic of slowly cooled lava.

Figure 4. Two scales of polygons are evident in this section of Fmap 37N007 (size 92 × 86 km). The larger polygons exist because of the intersection of a series of approximately NW-SE oriented wrinkle ridges. The morphology of the smaller diameter polygons is similar to extensional fractures.
The map view of a compressional fault, such as a wrinkle ridge, is more locally sinuous, but generally exhibits a unidirectional path across the landscape. In particular, we focus on the sinuosity of the fractures at the scale of both the length of the entire fracture and at the scale of the individual segments of the polygons. Examples of wrinkle ridges are in Figures 3 and 4. In Figure 4, the smaller scale polygons appear to be extensional and the larger scale polygons are made up of intersecting ridges. We use the morphology of fractures that occur in areas where the stress regime is well understood to infer that of fractures making up polygons. For example, McGill [1993] illustrates a variety of features that are interpreted to be wrinkle ridges. He uses criteria such as the predicted convergence or divergence of compressional stress regimes around topographic highs and lows, as well as ponding of lava flows, to determine that fractures are in fact compressional. Here we cannot use the same range of criteria, but instead must rely on morphologic similarity to fractures in Magellan radar data that have been unequivocally identified as extensional or compressional. It should be noted that there is likely to be a bias toward identifying the very small diameter polygons as extensional. When the fracture segments are very short, any sinuosity may not be resolved. Based on these morphologic characteristics, we interpret the polygonal fractures in Figures 1, 2, 7, 8a, and 9 as likely resulting from extension and those in Figures 3, 10, 11, 12, and 13 as likely formed by compression. However, we note that interpretation based on morphology alone is non-unique and invite others to make their own assessment.

In some areas (e.g., Figure 10), the fractures forming polygons have the locally sinuous characteristic of compressional fractures, but form equant polygons in many areas. This is in contrast to other areas categorized as compressional where the sinuous fractures have a dominant orientation. This suggests that the sinuous fractures may result from reactivation of polygonal fractures originally formed under extension followed by contraction under an isotropic compressional stress field. Reactivation could also account for the fact that some fractures are unusually wide and appear braided, as is seen in Figure 10. Overall, the fractures in Figure 10 have some characteristics of both extensional and compressional fractures.

Each of the areas containing polygons was classified as having ridges, troughs, or both, based on morphology. Where there are both ridges and troughs, the approximate percentage of each type of features was estimated. If we assign all of the area or a fraction of the area in each location to ridges or troughs, ~15% of the area containing polygons have a compressional morphology and ~85% have an extensional appearance. There are 56 areas that include polygons with evidence for compressional ridges. Of those areas, approximately 1/3 occur in association with coronae or corona-like features (Figures 12 and 13).

### 3.6. Flow Boundaries

We examine the relationship of polygons to flow boundaries in order to investigate the hypothesis that polygons form on cooling lava flows. We find that polygons are typically not confined to individual lava flows. We identify 22 locations where polygonal patterns distinctively cross flow boundaries. Figure 11 shows such an area. Two adjacent flows are recognized by their contrasting surfaces that are bright and rough, then dark and smooth, respectively. Polygons cross the boundary between both flows (arrows a). Although we recognize that a single flow can have both rough and smooth surface characteristics, stratigraphic relationships are used in an attempt to separate individual flows. When crossing flow boundaries, polygon patterns exhibit the same characteristics (size, orientation, width of the fractures) on both sides. This observation suggests that in these areas cooling of a single flow does not control the size and location of polygons. Rather, polygon-forming deformation must extend to greater depth than that of individual flows, and rocks of different relative age have deformed similarly. This finding is consistent with the large areal extent of many identified polygon zones.

Additionally, we identify 20 locations where polygons terminate at a flow boundary. Figure 8a displays such an area (04N246) in the western part of the image, a smoother, radar-dark flow interrupts the polygons. Polygons are observed again close to the western edge of the picture. We propose that in this location the polygonal fractures formed first. This fractured surface was then partially flooded by the smooth flow in the western part of the image. Our hypothesis is supported by altitude despite the low resolution of the data (5–8 km/pixel): the smooth (radar-dark) flow corresponds to slightly higher altitude points (brighter in the altitude image displayed in Figure 8b), than the rough terrain fractured by polygons. Additionally, our hypothesis is consistent with the fact that the polygons observed close to the western edge of Figure 8a have the same characteristic size as those existing in the eastern half of the image. Therefore, the smooth terrain could have formed last and covered preexisting isotropic polygonal fractures. Similarly in other areas where the polygons terminate at flow boundaries, younger flows cover and truncate older polygonal features.

Additionally there are many areas where small-scale flows appear to terminate along a fracture. These small-scale flows cannot be identified by their flow boundaries, but rather by changes in radar brightness. For example, in Figure 1, there are a series of darker patches, some of which may have associated pits. Some of these flows appear continuous across fracture boundaries, while others are confined within...
Figure 6. Global distribution of polygon locations overlaid on a gray scale topographic map. The size of the symbol indicates the areal extent of each polygon location (not to scale). The color indicates the average size of the polygonal patterns in each location. Squares indicate those locations that were previously identified, circular symbols were first identified by our analysis.
a set of fractures. Those that cross the fractures are either younger than the fractures or have been able, at least locally, to flow across a boundary. In other cases the fractures have caused the flows to terminate.

### 4. Relationship to Other Geologic Features

#### 4.1. Shield Fields

[29] Small volcanic cones are frequently associated with polygons. In 133 of our 204 identified areas, polygons are associated with volcanoes and exhibit a range of relative age relationships. Figure 7 (Fmap 29N142) is an example of a suite of features common on Venus where volcanoes apparently form both before and after the nearby polygons. It is apparent in many of these areas that the relative age relationships are highly complex, and the volcanoes, lava flows and small- and large-diameter polygons formed together, their stratigraphic relationships intergrading through time. The volcano indicated at a features several radial faults on the side of the volcano, leaving only the summit intact. Conversely, both volcanoes indicated by arrow b “cover” small lineations or polygons, as do several
other volcanoes in this region. Polygons with a diameter of 1 km surround the volcanoes, ending at the volcanic cones. This suggests that extensional stresses driving polygon formation propagate along the surface and are deflected slightly by and encircle the pre-existing cone. These particular fractures exhibit the same general morphology as faults located at a distance from the volcanoes (Figure 7, c), therefore their formation is probably not related to lava flows from the volcanoes. A few thin, linear, parallel, SW-NE oriented fractures that locally widen into graben at d appear contemporaneous. An example of a patch of gridded terrain is evident at e, as discussed below.

Figure 8. A portion of Fmap 04N246 (size 64 × 49 km) is shown in Figure 8a. Where polygons are visible, they have a uniform diameter. In the right central section of the image, polygons crosscut a darker unit, possibly an older flow unit. In the left central section, a younger, darker flow unit containing several small shields is superimposed on the polygons. The topography shown in Figure 8b (bright areas are high) is consistent with this stratigraphic interpretation. The area with the younger flow is higher standing than adjacent flows where polygons are still visible.

Figure 9. Polygons occur on lava flows embaying tessera (Figure 9a, from Fmap 27N079, dimensions 77 × 82 km). The variation in polygon size may reflect underlying topography and resulting differences in lava flow thickness. In Figure 9b, another area from Fmap 27N079, polygons are in embayed regions in the interior of a tessera block (dimensions 74 × 80 km).
4.2. Coronae and Corona-Like Features

Significant numbers (52) of polygon fields are associated with coronae and corona-like features (see Figures 12 and 13). Of these, approximately half of the locations contain previously identified coronae [DeLaughter and Jurdy, 1999; Stofan et al., 2001], including three type 2 coronae with partial fracture annuli [Stofan et al., 2001]. Some features that we identify as coronae are less than 50 km in diameter and were probably overlooked in other surveys. A few features are arachnoids, which are characterized by a radial set of compressional ridges that typically extend 10s to 100s of kilometers out into the surrounding plains, have depressed interior topography and an absence of volcanism [Head et al., 1992; Aittola and Kostama, 2000]. Concentric fractures are also present, but are less prominent than in coronae. Polygons at coronae and corona-like features can occur anywhere with respect to the corona rim: inside the rim, outside the rim, or only on the rim. In the majority of cases, the polygons extend well beyond the rim. Most polygons in coronae and corona-like features are located between large radial fractures (Figure 12). Most of the segments of the polygons are roughly radial or concentric to the corona, indicating that they are likely to have formed at the same time as the fractures that define the corona. Polygons located both inside and outside a corona or arachnoid commonly have the same characteristic dimensions and fracture widths (Figure 12). Polygons within coronae are often associated with small shield volcanoes (Figure 13). In this example, polygons are confined mainly to the interior. In some locations, the polygons are not oriented with respect to the corona. For example, in Fmap 21N100, the fractures are not oriented in a pattern that is radial or concentric to the corona. Instead, some polygons orient parallel to fractures that crosscut the corona. The area containing polygons is almost always much larger than the associated corona diameter. Figure 14 plots the aerial extent of polygons versus associated corona diameter, as defined by the maximum width of the fracture annulus. For these areas, the median corona diameter is 110 km, whereas the value for the median diameter of polygon fields is 250 km. In only four instances are the polygons confined to the interior. For the majority of cases where the polygons appear to be contemporaneous with the corona formation, the stress field responsible for the forming the polygons extends well beyond the circular annulus and in some cases beyond the radial fractures.

4.3. Tessera

Polygons are associated with tesserae in 37 locations. Tessera consists of complex, very rough, radar-bright ridged
terrain with more than one set of intersecting fractures [e.g., Hansen et al., 1997, and references therein]. Tesserae terrains occur in both high plateaus with diameters of thousands of km and in small, isolated patches in the plains. Polygons are typically associated with small, isolated, radar-bright patches of terrain surrounded by smoother plains rather than with the large plateaus. Polygonal terrain and tesserae are interspersed with polygonal patterns covering the surrounding smooth plains until truncated at the contact with adjacent tessera (Figure 9a). In some locations the polygons occur on small, interior regions that have experienced volcanic flooding (Figure 9b). The polygons are clearly younger than the tessera, as they form on plains material which emays the tessera. In few areas (Fmaps 10S040, 15N289, and 25N080) the polygon size locally decreases close to the tessera edge. The apparent change in diameter may reflect a decrease in the thickness of the plains unit as it approaches the edge of the tessera.

4.4. Wrinkle Ridges

[34] Wrinkle ridges are associated with polygons in 41 locations, as in Figures 3 and 4. Wrinkle ridges are long, sinuous, low hills which on Venus typically are 1–5 km wide and several hundred kilometers long, with spacings of 20–40 km [Hansen et al., 1997; Banerdt et al., 1997; Bilotti and Suppe, 1999]. Wrinkle ridges are compressional features formed as a surface expression of subsurface reverse faults [Plescia and Golombek, 1986; Golombek et al., 1991]. Watters [1991] suggests that they could also be caused by subsurface compression and buckling without actual faulting. On Venus wrinkle ridges are evident on over 40% of the plains [Bilotti and Suppe, 1999]. In many regions wrinkle ridges maintain a continuous orientation perpendicular to the topographic and geoid slope for 100s of kilometers and are believed to form as a result of downslope compressional stress [Banerdt, 1986; Sandwell et al., 1997; Bilotti and Suppe, 1999].

[35] Compressional stresses caused by heating of the surface in response to climate change has also been proposed to explain wrinkle ridges [Solomon et al., 1999; Anderson and Smrekar, 1999].

[36] An additional stress field is required to produce the preferred orientation typical of wrinkle ridge sets [Solomon et al., 1999]. In some areas the orientation of

Figure 11. Section of Fmap 77N355, with a size of 66 × 53 km. In locations a, the polygons cross an apparent flow boundary. A younger volcano covers preexisting polygons at location b.
elongate, or slightly elongate polygons is subparallel to nearby wrinkle ridges (e.g., Figures 3, 12, and 13). Ages of these features with respect to one another is not clear because of the difficulty in determining if ridge orientation is controlled by preexisting polygonal fractures, or if the polygonal patterns are expressions of unusual ridge morphology and intersection. The observation that the ridges that form polygonal patterns are shorter and generally less continuous than classic wrinkle ridges suggests that a prior polygonal pattern may be controlling their location. Such a pattern is consistent with the deformation predicted [Anderson and Smrekar, 1999] by Bullock and Grinspoon’s [2001] climate evolution model. In this scenario, there is an episode of cooling, followed by heating, and a final cooling, corresponding to extensional, then compressional, then extensional stress regimes. This predicts that fractures forming polygons will be produced first, with subsequent ridges formed in response to the compressional phase reactivating the initial polygon structures. The effects of a second extensional phase could be difficult to identify. Assuming a fixed plate model of bending and the most likely scenarios regarding the level of heating, the strain produced by compressive stresses is only on the order of 0.1%. Although this value is much lower than the 1–5% estimated for wrinkle ridges [Banerdt et al., 1997], these estimates were obtained for much larger wrinkle ridges than the ridges that comprise polygons in this study.

4.5. Gridded Terrain

[37] Gridded terrain on Venus is defined as regions with two sets of long, straight, narrow, intersecting fractures that are closely and regularly spaced [Banerdt and Sammis, 1992]. The fracture pattern is characteristically uniform over very broad areas. Several formation mechanisms have been proposed: cooling of lava flows [Solomon et al., 1992], stress shadowing, and shear lag [Banerdt and Sammis, 1992]. Additionally, Anderson and Smrekar [1999] suggested gridded terrain may have formed in response to climate change-induced stresses in the presence of a regional stress field. Although the spacing between fracture sets is similar to that of polygons, gridded terrain differs from polygon fields in that the fractures always have a preferred orientation, whereas the orientation of polygonal fractures is typically isotropic. Additionally, the length of each gridded terrain fracture is much longer than individual

Figure 12. Arachnoid within Fmap 26N033. The image has dimensions of approximately 90 × 137 km. Polygons occur within the set of radial ridges, starting at the center of the arachnoid and out into the surrounding plains.
polygon sides. Gridded terrain is associated with polygonal patterns in 45 locations. These patches are much smaller than areas of gridded terrain previously identified [Banerdt and Sammis, 1992], extending over at most tens of km (see Figure 7 containing bits of gridded terrain in ellipse e). The largest identified area with both polygonal terrain and gridded fractures is in Fmap 20N334 [see Johnson and Sandwell, 1992, Figure 5]. The small local regions of gridded terrain may represent areas where the general stress field producing the polygons is modified by local features into a preferred orientation.

4.6. Impact Craters

[38] Polygons are evident within impact craters in three locations (Fmaps 25N025, 33N289, and 31N053). Polygons are not found in the surrounding terrain. These polygons are likely to have formed as the dark, smooth interior deposits, comprised of either volcanic flooding or impact melt [e.g., Herrick and Sharpton, 2000; Ivanov et al., 1992], cooled. Within the crater in Fmap 25N025, the largest polygons are

Figure 13. Corona located within Fmap 01S171, with dimensions 130 × 210 km. This is one of the few areas where the polygons are confined to the corona rim and interior.

Figure 14. Lateral extent of polygons as compared to the diameter of the corona with which they are associated.
located in the center of the crater, suggesting a deeper body of impact melt or lava flooding in the center.

4.7. Global Distribution

[39] The search for polygonal features included nearly all of the Fmap data and covered 94% of the planet. Images in a few high latitude regions contain too much noise to allow the algorithm to function properly. The global distribution of polygonal terrain appears non-random. Areas containing polygonal fractures are predominantly found on the plains north and west of Aphrodite Terra, to the south and southeast of Beta Regio and surrounding Atla Regio (see Figure 6). Polygons are nearly absent from the plains to the south of Aphrodite Terra (20°–70°S, 0°–180°E), and between Beta Regio and Ishtar Terra (40°–70°N, 240°–40°E). Many of the regions of polygonal fractures found in association with tesserae are located near Tellus Regio. Polygons observed in association with shield fields, coronae or corona-like features have no particular clustering. Those areas identified as containing wrinkle ridges in this study may differ in some cases from wrinkle ridges identified in global data sets [Banerdt et al., 1997; Bilotti and Suppe, 1999] as much of that mapping was done at the C1 scale, a factor of 3 lower resolution. In comparing the population of areas containing polygons to the global distribution of wrinkle ridges, there are a variety of relationships. Most of the polygons are located either in areas where there are no large-scale wrinkle ridges, in areas that have multiple sets of wrinkle ridges, or in areas that do not correlate with negative geoid. Most polygons thus form in areas either lacking wrinkle ridges or in association with atypical wrinkle ridges.

5. Implications for the Origin of Polygon Regions

[40] Three mechanisms have been proposed for the formation of extensional polygons seen in Magellan data: 1) cooling lava flows [Johnson and Sandwell, 1992], 2) cooling following heating above a subsurface intrusion [Johnson and Sandwell, 1992], and 3) cooling in response to climate change [Anderson and Smrekar, 1999]. Polygons large enough to be detected at Fmap resolution are very unlikely to have formed on the surface of cooling lava flows, as the flows would have to be implausibly thick and cool extremely slowly to generate polygons of the scale seen on Venus [Johnson and Sandwell, 1992; Anderson and Smrekar, 1999]. This conclusion is supported by our observation that polygons terminate at flow boundaries typically only where younger lava flows cover and obscure preexisting polygons. Perhaps the simplest argument against the cooling flow hypothesis is that it is unlikely that apparently contiguous polygon fields extending up to hundreds of kilometers with polygonal diameters up to several kilometers would deform only lava flows that are estimated to be less than 1 km thick. Thus the two most likely mechanisms for the formation of extensional, polygonal fractures are cooling following lithospheric heating from below or cooling as a response to climate change.

[41] Perhaps the best argument for a lithospheric heating mechanism is the large number of polygons found in conjunction with coronae or corona-like features (10%), small volcanoes (49%), or with both (14%). The size range of polygon regions, although highly variable, is also comparable to the size range of coronae and of volcanic shield fields. Type 1 coronae, which have fracture annuli that are more than 50% complete, have a mean of 258 km and a standard deviation of 153 km [Stofan et al., 2001]. Type 2 coronae, which have less than 50% fracture annuli, have a mean diameter of 234 km, with a standard deviation of 125 km [Stofan et al., 2001]. Shield fields consisting of clusters of small volcanoes (~20 km in diameter), range in size from 50–350 km across with a mode from 100–150 km [Crumpler et al., 1997]. However, these associations are not clear evidence for subsurface heating. There is only one location where the polygons decrease significantly in size away from the corona. This is at Nightingale Corona, which is discussed by Johnson and Sandwell [1992, Figures 2 and 3]. This pattern would be expected to form in response to a decrease in the amount of heating away from the center, but it is seen in only one location.

[42] Alternatively, the polygons found at coronae and corona-like features may be a result of deformation related to corona formation. However, polygons are found only in a small percentage of coronae, <5%, and are not consistent with the stress fields that form typical fracture patterns. In some cases they may simply overprint the adjacent plains. Polygons may result from the formation of arachnoid features, where both the radial fractures that characterize this class of features and the polygons extend out well beyond the circular fracture annulus. Arachnoids are commonly topographic depressions, which could produce both the radial and polygonal fractures (Figure 12). It seems probable that the two types of fractures form simultaneously. Polygons would be unlikely to form second as an isotropic stress field would be disrupted by the long, closely spaced radial fractures. Additionally, many of the polygon segments are roughly radial or concentric (Figure 12), consistent with the same stress field.

[43] Nearly half of the polygons exist in association with small shield fields. At least 647 small shield fields occur on Venus [Crumpler et al., 1997], with ~20% of these regions containing polygons. If polygons are formed by climate change, plains with shield fields may have been locations with mildly extensional stress fields and thus may have favored polygon formation. It is possible that climate change-induced surface heating may have produced both surface deformation and enhanced volcanism by increasing interior temperatures [Phillips et al., 2001]. Certainly if both shield fields and polygons, which are at least locally contemporaneous, are both a manifestation of climate change, the effects are quite widespread. In a study of the stratigraphic age of 179 shield fields with respect to the surrounding plains, Addington [2001] found that the majority of shield fields postdate regional plains emplacement or contain some constructs that postdate the surrounding plains. This is consistent with a scenario in which most plains form in a major resurfacing episode that leads to a climate change event, which in turn produces a large number of shield fields and polygonal terrains.

[44] Several factors are consistent with the hypothesis of polygons forming during cooling induced by climate change. A little over a quarter of the polygons form in regions that have no apparent source of heating. Although
most polygons are associated with either shield fields, coronae, or corona-like features, the majority of shield fields, coronae, or corona-like features do not contain polygons. This implies that polygons are not a typical product of the formation of these features. Rather the formation of these features may produce an extensional stress field that favors polygon development induced by surface heating. The range of diameters, including both small-scale and large-scale polygons, is consistent with stresses predicted by climate change. The occurrence of a global temperature change, or multiple changes, is consistent with a narrow range of polygon sizes.

In addition to the classic polygons that appear to be formed in extension, 15% of polygons have morphologies that are more consistent with compressional ridges than extensional fractures. These ridges are much shorter and narrower than typical wrinkle ridges. Both gravitational forces on topographic slopes and heating by climate change have been suggested to produce the required compressional stresses to form wrinkle ridges. Solomon et al. [1999] proposed that wrinkle ridges are the product of both downslope gravitational forces, which produced a constant orientation over long distances, and heating caused by climate change, resulting in polygon formation over a narrow time period. Bastilevsky and Head [1998] and Head and Bastilevsky [1998] argued that stratigraphic relationships are consistent with wrinkle ridges forming in a relatively narrow geologic time period. Others have disputed this interpretation [Hansen and Williams, 1996; Guest and Stofan, 1999]. Anderson and Smrekar [1999] found that the stresses needed to produce wrinkle ridges were at the upper limit of those likely produced by climate change. The smaller ridges observed in this study may have been formed by climate-induced heating. They are observed both as relatively elongate polygons in association with larger wrinkle ridges (Figures 3 and possibly 4) and as more equant polygons (Figure 10). Those with a preferred orientation commonly have two scales and spacings of ridges (Figure 3). The smaller ridges have a typical spacing of 1–2 km while the larger fractures occur at 10–25 km. These two scales of deformation are predicted by climate change-induced heating. The small-scale polygons are a result of shallow brittle failure; the larger scale ridges are a result of deeper ductile deformation. Although the strain predicted for the ductile deformation in particular is very low (~0.1%), the features observed here are smaller than typical wrinkle ridges and may be consistent with these small values. As suggested by Solomon et al. [1999], a regional stress field may suppress the formation of extensional features. That is consistent with the fact that in these areas the polygons have a preferred orientation.

A climate change scenario can explain polygons that are more equant in the absence of a regional stress field. The climate change scenario of Bullock and Grinspoon [2001] predicts first cooling followed by heating, indicating extension may follow compression. As compressional deformation requires greater deviatoric stresses to produce failure, compressional features are harder to produce via climate change related heating. Anderson and Smrekar [1999]. The ridge-like features that form polygons (Figure 10) would be predicted in an area that first forms polygonal cooling fractures and then experiences reactivation in response to homogenous compressional stress caused by thermal expansion. Shallow contractional strain could reactivate and propagate along preexisting polygonal fractures. This also appears to be the case in Figure 4, where larger scale ridges also form polygons, implying deeper ductile deformation as well.

Although the observations of polygon characteristics appear to be most consistent with a climate change origin, the question remains as to why polygons cover only 2% of the surface. Due to the homogeneity of surface temperature caused by the dense Venusian atmosphere, climate change produces globally uniform temperature variations. There are a variety of possible reasons for the limited areal extent of polygons. Certainly some polygons have been covered by subsequent lava flows (see Figure 8). Analyses of impact crater data indicate that there is a wide distribution of ages of plains units, and that volcanism was not limited to a single era in the history of Venus [Hauck et al., 1998; Campbell, 1999]. Another plausible explanation is that the polygons that we are seeing are only the larger polygons. In numerous places the size of the polygons decreases from a clearly resolvable size down to the limit of resolution. It is possible that the polygons we are able to see are only those that are larger due to additional favorable conditions such as a regional extensional stress field, a weaker surface unit, or additional volcanic heating.

The formation of polygons may also be limited by the need for a homogeneous stress field. Homogeneity is needed both horizontally over 10s of kilometers and vertically in the upper several kilometers of the crust. The plains contain a wide range of deformation features [Banerdt et al., 1997], indicating small outliers of tessera material that suggest widespread, buried tectonic features [Hansen et al., 1997]. It is possible that layers of volcanic features may disrupt the stress field as well. Certainly large volcanoes influence the stress field well beyond their diameter. Possibly individual layers of flows may cause enough vertical variation in the strength of the crust to disrupt the formation of polygons locally. Mildly compressional stress fields, such as can be produced by gentle topographic slopes [Banerdt, 1986; Sandwell et al., 1997; Bilotti and Suppe, 1999] may suppress the formation of polygons. Last, in addition to polygonal terrains, features such as shield fields, grided terrains, and wrinkle ridges may also be manifestations of climate change [Anderson and Smrekar, 1999; Phillips et al., 2001].

A final important question is whether or not the polygonal terrain forms a stratigraphic marker. Certainly Venus appears to have experienced a period with a very high resurfacing rate consistent with volcanic outgassing volumes capable of producing climate change [Bullock and Grinspoon, 2001]. If all polygons formed in this event, they should represent a stratigraphic marker. Such a hypothesis may be very difficult to test given that small areas typical of polygon fields on Venus contain insufficient numbers of impact craters for dating reliability [Plaut and Arvidson, 1988; Campbell, 1999]. However, it is a hypothesis that should be considered by mappers examining individual areas. Preliminary modeling work also suggests that more limited volcanic events may also be capable of producing
significant temperature excursions [Bullock et al., 2000]. If this is indeed the case, climate change could have produced several polygon-forming events.

6. Summary

[51] We identify over 170 new areas of polygonal fractures on the plains of Venus, bringing the total number of such areas to 204. These features are typically equant, have fracture spacings of 1.8 ± 0.9 km, and polygon field diameters of 30 to 600 km. Polygons are distributed over most of the planet, with a few large areas lacking any polygons. On the basis of their morphology, the majority of the polygons appear to consist of extensional fractures. Polygons can consist of intersecting ridges as well. A small number (~45) of polygon fields are associated with large wrinkle ridges. Approximately half of identified polygons are associated with shield fields. Where it is possible to infer stratigraphy, the formation of shields and polygons apparently overlaps through time. Polygons are also commonly associated with coronae and corona-like features (22%), with half of these areas also including shield fields. Polygons are also identified on lava flows embodying tessereae terrains, although these polygons clearly post-date the tesserae and are likely to have no genetic association. There are no examples of polygons terminating at the edges of volcanic flows, except where later flows cover polygons, or flows embay higher topography.

[52] Although the classic mechanism for polygons formed under extension on Earth is cooling of lava flows, the scale of the features observed on Venus renders this interpretation very unlikely [Johnson and Sandwell, 1992; Anderson and Smrekar, 1999]. Additionally, polygons are not observed to terminate at the boundary of flow fields. The most likely explanations for polygons formed under extension on Venus are contractional stresses resulting from 1) cooling of the lithosphere following heating and thinning of the lithosphere, and 2) cooling due to reduced surface temperatures caused by climate change. The large number of polygons found in association with shield fields and the smaller number found with coronae and corona-like features supports the local heating hypothesis. However, given that only a small percentage of shield fields and coronae contain polygons it is possible that these regions simply represent those active during a climate change event. Any extensional stresses associated with these features may have added to the surface temperature-induced extension. Additionally, a significant decrease in polygon size away from the center of the corona is observed only at Nightingale Corona. This decrease in size would be expected to occur as heating declines outward from a corona center if the polygons formed solely in response to corona formation. Further, polygons usually continue more than one corona diameter out into the plains.

[53] A number of factors supports the climate-change hypothesis. First, some polygons occur in areas where there is no apparent source of heating in the form of volcanoes or coronae. The range of polygon diameters, including both small and large-scale diameters, is predicted by models of the tectonic effects of climate change [Anderson and Smrekar, 1999]. Additionally, climate change-induced temperature fluctuations include both cooling and heating and can thus account for polygons formed under extension and compression. The smaller percentage of polygonal ridges, assumed to form under compression, is not unexpected considering the greater strength of rock under compression than that under extension.

[54] Although the climate change model can explain many characteristics of polygons, the formation of polygons cannot be unambiguously attributed to this process. In addition to lithospheric heating or cooling, regional stress fields, such as those associated with arachnoid formation, may also form some polygons. Further progress may be made on this question by examining the hypothesis that regions of polygons represent one, or perhaps two, stratigraphic markers. The characteristics of other types of terrain, such as gridded terrain and wrinkle ridges, are also consistent with strain produced by climate change [Solomon et al., 1999; Anderson and Smrekar, 1999]. One goal of this paper is to urge mappers to consider carefully the role of polygons within local stratigraphy. Further study of how the shield fields, coronae, corona-like features, and wrinkle ridges associated with polygons differ from other such features may also offer some insight into the mechanisms forming polygons and the possibility that climate change has occurred on Venus. Similarly, large regions that lack polygons may have unique characteristics, possibly indicating more recent resurfacing or regional stress fields.

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