UTOPIA PLANITIA: OBSERVATIONS AND MODELS FAVORING THICK WATER-DEPOSITED SEDIMENTS. Debra L. Buczkowski and George E. McGill, Department of Geosciences, University of Massachusetts, Amherst, MA 01003, (dbucz@geo.umass.edu, gmcgill@geo.umass.edu).

Introduction: One of the most important issues of martian geological history is whether or not there have been bodies of standing water on the surface at one or more times in the past. Because of its size and the volume of water involved, the most important of these putative bodies of water is the "ocean" inferred to have occupied the northern lowland at various times during martian history [1,2,3,4,5]. Assessing the validity of hypotheses for a northern paleoocean involves determining the nature and thickness of the deposits that overlie the ancient Noachian floor of the northern lowland. Data from Mars Global Surveyor and Mars Odyssey can address the thickness and origin of these deposits in several ways, including evaluating proposed shorelines, comparing depositional ages with times of outflow channel activity, modeling behavior of the deposited materials, mapping associations between potentially diagnostic structures and lowland topography, and inferring deposit thickness from properties of these structures. The approach here is to summarize observations and models for the post-Noachian evolution of Utopia Planitia that point toward the deposition from water of sedimentary deposits forming a layer that must be >390 meters thick where this thickness can be directly estimated, and that very likely is as much as 2-3 km thick in places. Demonstrating that these deposits are water-laid sediments would provide very strong evidence in favor of an ocean. Most of our effort has focused on those parts of the putative sedimentary deposits that are deformed into giant polygonal terrain, especially in Utopia Planitia where the association of polygonal terrain with lowland topography is most clear.

Geologic Setting: Most of Utopia Planitia is underlain by the large Utopia Basin, originally inferred from the distribution of knobs and mesas defining the main basin ring, and from the distribution of giant polygonal terrain that rings the inner part of the basin [6]. Most of the lowland deposits within the Utopia Basin are mapped as the Vastitas Borealis Formation, which is divided into 4 members defined by means of associated structures or landforms [7]. Primarily because of superior resolution and clarity of Viking images, and absence of obscuring polar surface processes, the stratigraphy within the basin is best displayed across its southern flank. To the south, adjacent to the dichotomy boundary, the ridged member of the Vastitas Borealis Formation is exposed [7]. This unit corresponds to an Early Hesperian ridged plains unit mapped over much of the lowland [8]. Northward an Amazonian knobby plains unit is mapped [7]. The knobs are almost certainly Noachian inliers, and their distribution was used to define the main ring of the Utopia Basin [6]. The young plains materials surrounding the knobs overlie and partially obscure the ridged plains member of the Vastitas Borealis Formation exposed to the south. However, the ridges are still visible through the young plains in detrended MOLA altimetry [8]. Northward, the ridged plains are overlain by the Grooved Member of the Vastitas Borealis Formation, which is characterized by giant polygons. Except where covered by a tongue of Amazonian materials derived from Elysium Mons [7], the Grooved Member (= polygonal terrain) occupies most of the central part of the Utopia Basin [7]. Crater counts on Utopia polygonal terrain yield an age of Late Hesperian [9,10], consistent with the stratigraphic sequence inferred from geology and topography. All of the craters used to date the polygonal terrain are superposed on the troughs defining the polygons, and thus these structures also must be Late Hesperian in age.

Observations: A number of observations support a water-laid sedimentary origin for the materials of polygonal terrains. Polygonal terrains occur in the lowest parts of the northern lowland, the most logical places for water to pond and sediments to accumulate if oceans or large lakes did occur [11,6,12]. Craters superposed on these terrains are dominantly characterized by fluidized ejecta, generally believed due to significant volatile content in the target material [13]. The upper elevation limit for polygonal terrain exposures along the south flank of the Utopia Basin occurs close to an elevation of -4350 meters [14], approximately coinciding with a topographic terrace along the flank of the Utopia Basin that has been interpreted to be a paleoshoreline [15]. Other terraces have been inferred at elevations of -3650 m, -4200 m, and -4600 m [5], the first only ~100 m higher than the mean elevation of inferred global shoreline “contact 2" [1]. Most of these terraces can be traced for only a few 10's of km around the basin flanks. In addition, a large and more laterally continuous bench occurs at -4700 m [10]. Finally, the Late Hesperian age of Utopia polygonal terrain coincides with the time of most outflow channel activity [16].

Most of the Utopia polygonal terrain consists of troughs of varying length, depth, and width that form an irregular pattern that most closely resembles the “irregular random” pattern defined by [17]. The geometry of these troughs indicates that they are degraded grabens. Within the Utopia polygonal terrain are several 10's of grabens that are circular, and our research indicates that they exhibit properties supporting deposition of polygonal terrain material from water, as will be discussed below. These circular grabens are interpreted to overlie the rims of buried impact craters [18,19]. Presumably these buried craters were superposed on the older, Early Hesperian ridged plains unit [8]. It is straightforward to estimate the minimum thickness of material covering the buried craters; the thickness must exceed the height of the rims of the buried craters, as estimated using morphometric equations for martian craters [20]. In Utopia Planitia, the diameters range from 7 to 32 km, and thus ridge height and hence minimum cover thickness ranges from 190 to 390 m. Even the smallest value in this range exceeds the ~100 m estimate of cover thickness in [8], and thus we do not believe that their result can be correct. The diameters of areas enclosed within circular grabens exhibit no systematic areal pattern; that is, the largest values seem randomly distributed throughout the entire population, indicating that the minimum thickness of cover required to just bury the craters lying below circular grabens is close to 390 m throughout the Utopia polygonal terrain.

Actually, the minimum thickness must be greater than crater rim height in order to permit formation of a graben in the cover over the rim. The thickness of cover needed for a graben to develop depends on the assumed fault dip angle, and on the initial width and sub-surface geometry of the graben. For likely values of these parameters, the additional thickness required is at least several hundred meters.

Modeling: A number of models have been proposed to explain the giant polygons, based on methods of forming polygons on Earth. These models invoke such familiar processes as the cooling of lava [21,22,23], frost wedging [24] and the desiccation of wet sediments [23]. However, the giant martian polygons are two orders of magnitude larger than the largest polygonal structures on Earth, and none of the above processes can be scaled up to the martian dimensions [25]. Two models [19,9,26] try to explain the large scale of the martian polygons by suggesting that they form in a cover material that is tectonically bending and compacting over an uneven, buried surface. However, while these models can explain the location of the troughs bounding the polygons, the surface bending strains produced are not sufficient to explain the width and depth of the troughs [9]. It has been proposed [14] that rebound of the crust beneath the Utopia Basin as a result of drying of a northern ocean created roughly isotropic extension in Utopia Planitia. They cited Pechmann [25], who estimated that an uplift of ~1 km would yield about 0.03% regional extension. For an average graben depth of 30 m and average graben spacing of 7 km [14] the regional extension required to form the grabens is ~1% for 60° fault dips and ~0.3% for 80° fault dips. Furthermore, a kilometer of rebound uplift would require loss of ~3 km of water, a factor of ~3 greater that the estimated maximum ocean depth within Utopia Basin [14]. Thus rebound would provide extension that is more than an order of magnitude too small to account for the grabens.

Differential compaction of polygonal terrain material can account for the needed extension [9,27,28]. That this process has occurred is indicated by two simple tests. A differentially compacting cover material will produce a surface relief that is dependent upon the thickness of the cover material, the relief of the basement floor it covers, and the average compaction throughout the cover layer. The percent compaction at any depth within the cover must be a function of the total overburden pressure. This means that percent compaction should increase with the depth of the cover deposit, and thus that the average fractional compaction should be proportional to cover thickness. If the circular grabens do overlie buried impact craters, then differential compaction models predict that they will bound topographic depressions, because total cover thickness will be greater over the centers of completely buried craters than over their rims. Since large craters

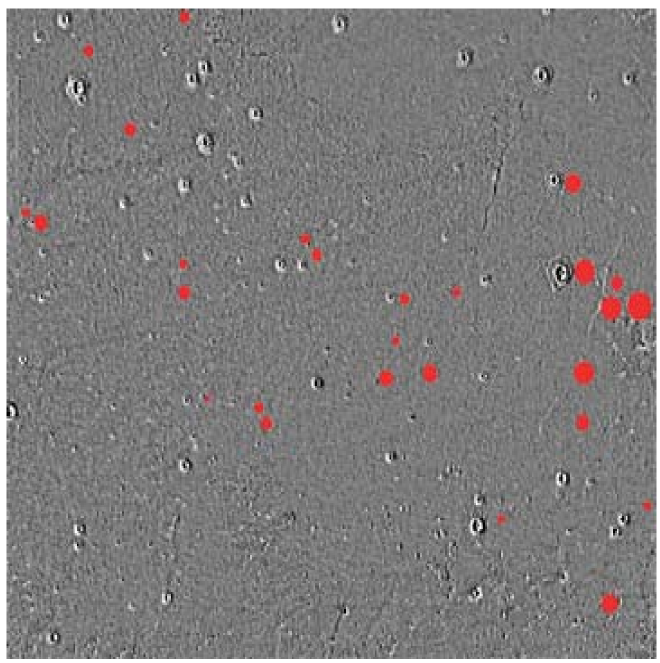

Figure 1. Location of 27 circular grabens on the southwest flank of the Utopia Basin. 21º-33ºN, 241º-257ºW

are deeper than small craters, the models also predict that surface relief will be proportional to ring fracture diameters. Studies of 27 circular grabens (Fig. 1) found on the southwest flank of the Utopia Basin [27,28] showed that these predictions hold true in Utopia Planitia (Fig. 2).

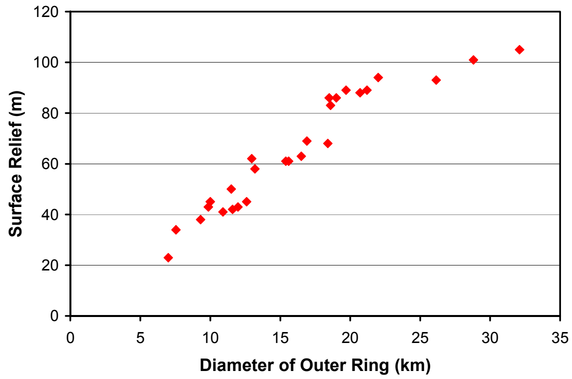

Figure 2. Diameter of the outer ring of circular grabens vs. the surface relief of the enclosed depression, as determined by MOLA. Surface relief is defined as the absolute value of the difference between the highest point on the ring's rim and the lowest point it surrounds.

Most of the circular grabens in southwest Utopia Planitia are comprised of two concentric nested rings. Tectonic bending of the cover material would increase the probability of fracturing over a drape anticline formed over a buried crater rim, but this should only produce one graben. And yet, of the 27 circular grabens studied, only two consisted of a single ring; the remaining 25 are double. The spacing between the concentric rings does not correlate with diameter of the circular grabens (Fig. 3) but does correlate with its proximity to the center of the Utopia basin (Fig. 4) [28]. Many researchers [e.g. 29] have inferred that cover thickness should increase towards the center of the basin, thus suggesting a correlation between ring spacing and thickness of cover material. In addition, the average depth of polygonal terrain grabens increases towards the center of the Utopia Basin [14], suggesting a relationship between graben depth, cover thickness, and distance from the center of the basin. Numerical models show that the differential compaction of a cover material over a crater rim produces two regions of maximum tangential stress at the surface, one inside of the crater rim and one outside [30]. These regions, where we would expect grabens to form, move away from each other with increasing cover thickness. The modeling results thus match the observations in Utopia Planitia. To produce graben spacings within the obser-

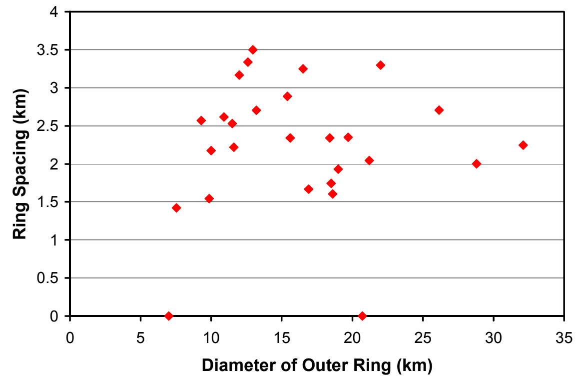

Figure 3. The spacing between the two ring grabens vs. the diameter of the outer graben.

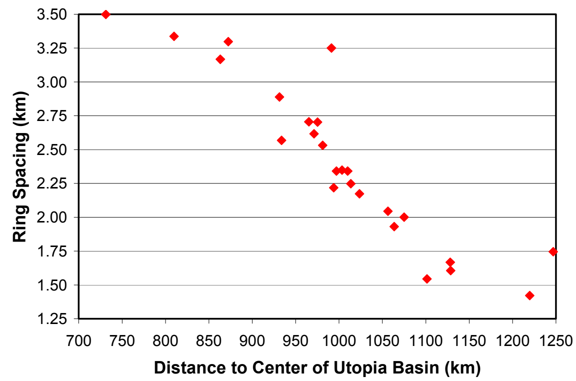

Figure 4. The spacing between the two ring grabens vs. the distance to the center of the Utopia Basin. Center of the Utopia Basin is assumed to be 44ºN, 113ºE, the center point of the 17º circle that circumscribes the Utopia polygonal terrain [9]. Alternatively, the lowest topographic point as determined by MOLA [15] is located at 45ºN, 112ºE. Although there are small variations in the plot when using this location, the trend is the same.

ved range (1.4-3.5 km), preliminary numerical models require cover thicknesses within the 1-3 km of maximum cover estimated by [29].

Discussion: Both the modeling and the surface relief observations of circular grabens strongly support differential compaction in Utopia Planitia. This compaction, however, needs to produce sufficient horizontal strain to create the observed polygonal troughs. Wet soils shrink as they dry because the surface tension of the water pulls the grains toward each other. The resulting strain due to volume loss can easily be large enough to account for the dimensions of the polygonal fractures [9]. Studies of polygonal fault systems in Lower Tertiary mudrocks in the North Sea Basin determined that the bulk extensional strains that caused faulting are a component of the compaction process [31]. Polygonal faulting due to compaction-related extension has now been identified in fine-grained sedimentary rocks of numerous globally distributed basins [32,33,34]. These studies indicate that the North Sea polygons accommodated radially isotropic extensional strains of up to 20% [31]. Large volume air fall or surge volcanic deposits also shrink as they cool, especially if they weld, but this is predominantly accommodated by vertical compaction with only minor horizontal shrinkage [35]. Thus cooling volcanics will not provided the horizontal extension needed to account for the grabens bounding the giant martian polygons. Thus the robustness of the support for the differential compaction model of polygon formation from observations, numerical modeling, and Earth analogues, strongly implies that the cover material in Utopia Planitia was deposited from water..

Conclusions: Evidence that polygonal terrain material, and perhaps material of other members of the Vastitas Borealis Formation as well, is sedimentary and water deposited is varied and strong. This evidence ranges from global temporal or spatial associations with outflow channels, possible shorelines, deep topographic depressions, and fluidized ejecta craters to detailed geologic, geometric and kinematic characteristics of polygonal terrain structures. Polygonal terrain, which corresponds to the Grooved Member of the Vastitas Borealis Formation, must be on the order of 1-3 km thick, with thickness increasing systematically from the flanks towards the center of the buried Utopia Basin.

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