Figure 3. Circular gray scale image of the slope azimuth distribution for the 180°E to 360°E hemisphere of Mars. Lighting is from the north (solar azimuth=0°). Projection is Sinusoidal.

image shown in Figure 4 uses an incident insolation calculation (Donker & Meijerink, 1997) to determine the relative radiance (0.0 - 1.0) for each grid cell in the Martian DEM. The slope gradient and the slope azimuth of each grid cell along with the user selected solar azimuth (0^o - 360^o) and solar elevation (0^o - 90^o) are used to calculate the relative amount of solar radiation striking the Martian surface for any grid cell of the DEM. A linear scaling of the relative radiance distribution from minimum (GLV = 0 or black) to maximum (GLV = 255 or white) produces a Lambertian hillshaded image in which the plains now appear smooth and flat.

Other characteristics of the circular gray scale image shown in Figure 3 include the 'plastic-like' appearance of those regions, such as the flanks of the Tharsis shield volcanoes, where there is a systematic and smooth change in azimuth that defines the sides of the cones. Emphasis on every break or edge in the landforms, regardless of magnitude, is the hallmark of the circular grayscale display; no other mapping transformation that I have used produces this level of detail.

"Emphasis on every break or edge in the landforms, regardless of magnitude, is the hallmark of the circular grayscale display; no other mapping transformation that I have used produces this level of detail."

Tomographic Mapping

Tomography is a technique usually associated with medical X-ray scans of the human body. The New World Dictionary of the American Language (1984) offers this derivation - "*Tomo* is from the Greek *tomos* which means *a piece cut off*", and definition - "a technique of X-ray photography by

Figure 4. Hillshade image created by the linear gray scaling of the relative radiance distribution for the 180°E to 360°E hemisphere of Mars. Lighting is from the north with a solar azimuth=0° and a solar elevation=45°. Projection is sinusoidal.

which a single plane is photographed, with the outlines of structures in other planes eliminated". A procedure based on this definition was used to construct cardboard landform relief models (Eyton, 1986b) from computer-generated templates. This procedure has been modified to produce images generated from DEMs as horizontal transparent slices of the earth's surface that can be stacked in a three-dimensional volumetric black and white, or color, display.

Figure 5 shows a hillshaded image of Olympus Mons derived from the $1/64^{o} \times 1/64^{o}$ DEM (1000 x 1200) subset obtained from the Mission Experimental Gridded Data Records (MEGDR) as the MEGT45N090G. IMG data file (Planetary Data System Geosciences Node, 2002). The elevation range for the DEM was divided into nine equal-interval classes and those portions of the hillshaded image that fell into each elevation class were printed as separate images (see Figure 6) onto overhead transparency media. About nine or ten sheets appear to be the maximum number of transparencies that can be used in a stack; any more, and the additive density of the material makes it difficult to see detail on the bottom layers. The limiting number of sheets controls the number of elevation classes that are selected and in order to add contour lines equal interval classes are required. Table 2 shows the classes I chose to slice the elevations from the Olympus Mons DEM while adding contour lines at a 3000 m interval.

". . . the additive density of the material makes it difficult to see detail on the bottom layers. The limiting number of sheets controls the number of elevation classes that are selected and in order to add contour lines equal interval classes are required."

The overhead transparencies were attached to overhead transparency cardboard mounting frames and then stacked on top of each other in

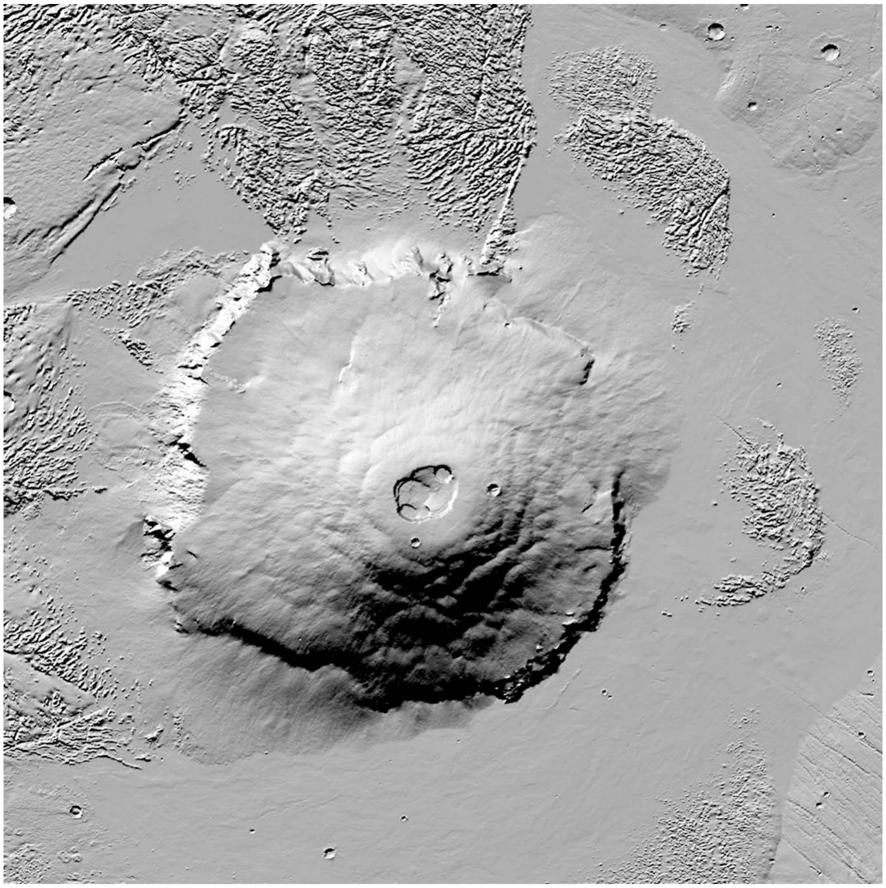


Figure 5. Hillshade image of Olympus Mons derived from the 1/64° x 1/64° resolution DEM. Lighting is from the northwest (solar azimuth=315°) with a solar elevation of 45°.

register to produce a mechanical volumetric model. Persistence of vision blends the individual layers into a continuous three-dimensional display that can be examined from any direction without the use of special viewing aids. The same procedure can be applied to other images, such as satellite scenes, land use maps, temperature distributions etc., registered to a DEM, to produce volumetric maps with black and white, or color, thematic overlays.

The principal drawback to this mapping approach is that the images printed on the overhead transparency material, when stacked, become difficult to see due to the additive density of multiple layers. A simple solution is to attach a white sheet of paper to the bottom of the stack and hold the display up to a light source. A better solution is to fix the display onto a small light box that is mounted at eye-height on a wall. Figure 7 shows a photograph of the Olympus Mons hillshade volumetric map attached to a 9 inch x 12 inch light box.

Several alternative production methods can be used to enhance, or solve problems, with these displays. For example, vertical exaggeration can be increased by simply adding a blank transparency frame between each image layer or slice; adding two or more blank transparency mounts between each image layer will produce a display with bright spacing that appears the equivalent of white contour lines. Problems with seeing the gaps between the layers can be reduced by adding black contour lines to the hillshaded image (or other images) with a contour interval equal to the elevation class interval used for slicing. Slightly overlapping slices with

"The same procedure can be applied to other images, such as satellite scenes, land use maps, temperature distributions etc., registered to a DEM, to produce volumetric maps with black and white, or color, thematic overlays."

". . . vertical exaggeration can be increased by simply adding a blank transparency frame between each image layer or slice . . ."

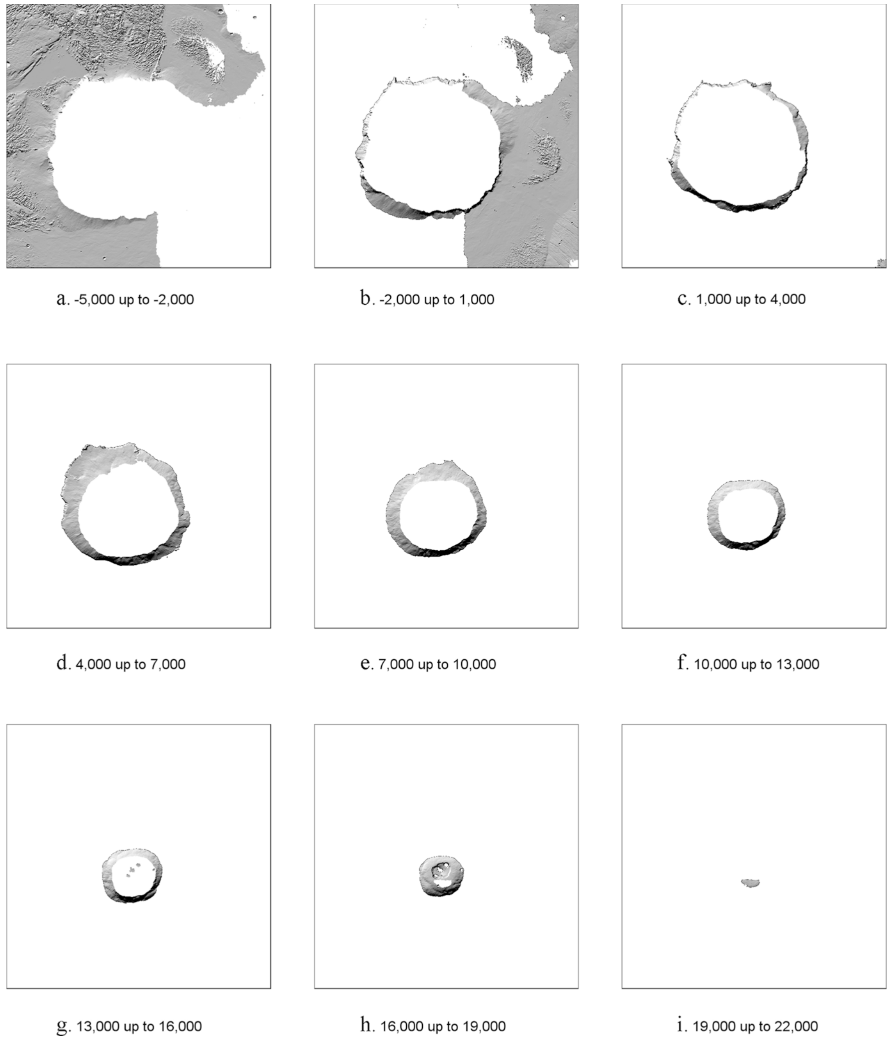


Figure 6. Slices of the hillshade image shown in Figure 5 using a reference location= -5000m and an elevation class interval=3000m were used to produce these nine images.

Elevation Class	Lower Class Limit	Upper Class Limit
1	-5000	<-2000
2	-2000	<1000
3	1000	<4000
4	4000	<7000
5	7000	<10000
6	10000	<13000
7	13000	<16000
8	16000	<19000
9	19000	<22000

Notes

The actual extremes for the Olympus Mons DEM are as follows:

Z-minimum = -3264 m

Z-maximum = 21229 m

The class interval for the tomographic slicing was set at 3000.

Table 2. Elevation Classes for the Olympus Mons Tomographic Map

feathering at the edges is another alternative for creating a smooth transition between the image segments of the display.

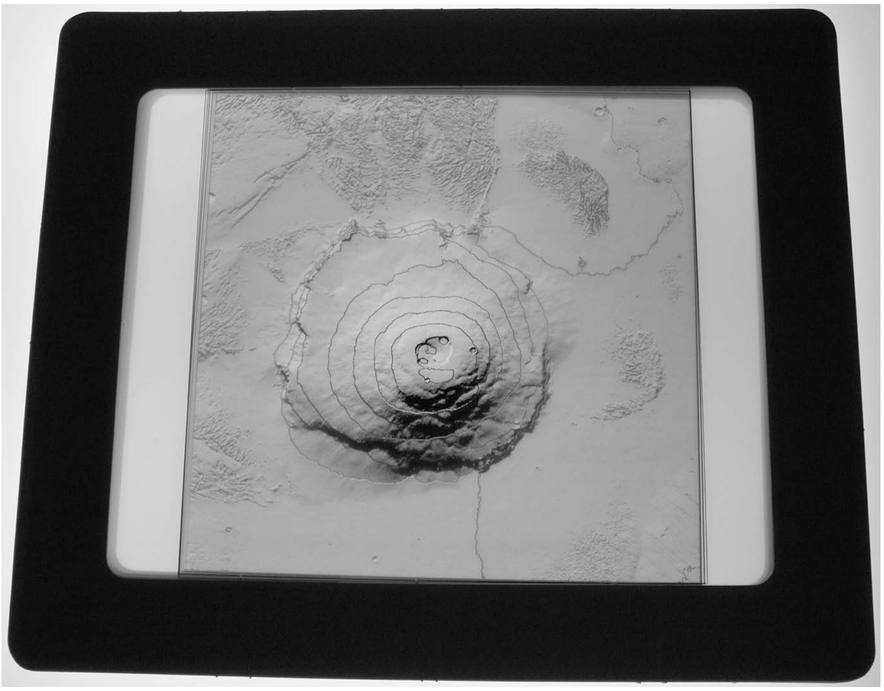


Figure 7. The nine image slices shown in Figure 6 have been attached to overhead transparency frames, interleaved with blank frames, and stacked in register to form the volumetric map displayed above.

Digital Distance Models

A transformation that converts the vertical height distribution of a DEM into a horizontal distance distribution that I call a digital distance model (DDM) provides the basis for a number of unique measurements and displays. Figure 8 illustrates how the process works using a small 3 x 5 DEM and the resulting 10 x 5 DDM. The small amount of easy to read FORTRAN code used to extract the DDM from the DEM is given as well. The algorithm may be more readily understood as a graphic (see Figure 9) that illustrates the relationship between the DEM and the DDM for the transformation of the first column of elevation values in the DEM, to the first column of distance values in the DDM. A subset of the Mars 1/64^{o} x 1/64^{o} DEM (1000 x 1200) found in the Mission Experimental Gridded Data Records (MEGDR) as the MEGT00N270G.IMG data file (Planetary Data System GeosciencesNode, 2002) centered on the Melas Chasma region of Valles Marineris was converted to a DDM (150 x 1200) then displayed as gray scale images to illustrate the process. Figure 10 shows a hillshaded image with a white line bisecting the valley walls that contain the Mellas Chasma where it opens to the north into Condor Chasma and then into Ophir Chasma. In order to obtain an unobstructed view of the valley wall north of the line, all elevations in the DEM south of the line were set to the elevation value occurring at the intersection of the line. The DDM was created by looking from the south of the modified DEM to the north. A slope gradient transformation was used on the DDM before gray scaling to produce the horizontal view shown in Figure 11a. The slope gradient

"A transformation that converts the vertical height distribution of a DEM into a horizontal distance distribution that I call a digital distance model (DDM) provides the basis for a number of unique measurements and displays."

GRID CELLS (COLUMNS)

		1	2	3	4	5	
	1	52.	68.	76.	30.	21.	
ROWS	2	36.	53.	32.	25.	21.	DEM (3X5)
	3	23.	34.	42.	21.	21.	

GRID CELLS (COLUMNS)

		1	2	3	4	5	
	10	0.	0.	0.	0.	0.	
	9	0.	0.	1.	0.	0.	
	8	0.	1.	1.	0.	0.	
	7	0.	1.	1.	0.	0.	
ELEVATION	6	1.	2.	1.	0.	0.	DDM (10X5)
CLASSES	5	1.	2.	1.	0.	0.	
	4	1.	2.	3.	0.	0.	
	3	2.	3.	3.	0.	0.	
	2	2.	3.	3.	2.	0.	
	1	3.	3.	3.	3.	3.	

```
C FORTRAN PROGRAM TO TRANSFORM EXAMPLE DEM TO DDM
C
      REAL*4 DEM(3,5),DDM(10,5)
      DATA DEM/52,36,23,68,53,34,76,32,42,30,25,21,21,21,21/
C
C ASSIGN PARAMETERS
      NROWS=3
      NCOLS=5
      NCLASS=10
      NCLASS1=NCLASS-1
      ZMAX=80.
      ZMIN=20.
      ZRANGE=ZMAX-ZMIN
C TRANSFORM DEM TO DDM
      DO I=1,NROWS
        DO J=1,NCOLS
          NZR=(ZMAX-DEM(I,J))/ZRANGE*NCLASS1+1.5
          DO II=NZR,NCLASS
            DDM(II,J)=I
          END DO
        END DO
      END DO
C WRITE OUT DISTANCE VALUES FROM DDM(II,J)
      DO I=1,NCLASS
        WRITE(*,'(5F5.0)') (DDM(I,J),J=1,NCOLS)
      END DO
      STOP
      END
```

Figure 8. The relationship between a DEM and an extracted DDM is presented using a small example data set. The FORTRAN code used to create the 10 x 5 DDM from the 3 x 5 DEM is listed below the diagrams.

for the DDM was determined using the zero distance plane as the base reference. For areas that show no terrain (above the top of the valley) the slope gradient as measured against the zero distance plane will be zero

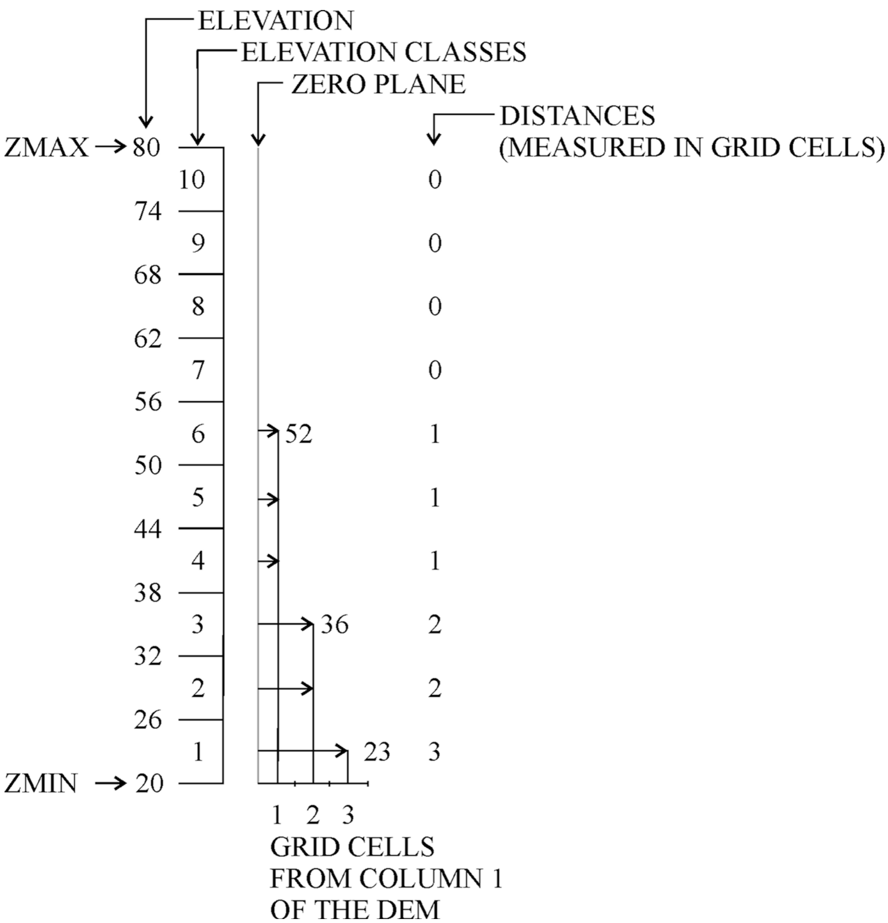


Figure 9. This graphic shows the relationship between the first column of the 3 x 5 DEM and the first column of the 10 x 5 DDM from a left side, horizontal point of view.

degrees and appears dark toned (black) in a gray scale map; slopes greater than zero will appear light toned.

The resulting display, which has an abnormal appearance, similar to that of a film negative image, can be altered by reversing the tones to produce the 'positive' image shown in Figure11b. Flat (as measured against the zero distance plane) or nearly flat areas will now be light toned and steeper areas will now be dark toned. This image has an ink-sketch quality that I believe portrays the landscape in a more normally accepted rendition.

Other transformations and mappings of the DDM can provide useful displays as well. Contouring the DDM will produce a series of cross-sectional profiles; gray scaling the DDM will produce a display that is reminiscent of the actual view, paintings, and photographs of the various foreground to background planes of terrestrial foothills and mountains when observed from afar. Parallax induction is another transformation that can be easily applied to a DDM to produce a unique graphic in the form of a stereogram. North and south looking DDM subsets (150 x 290), centered on the arrows visible in Figure 10 were used to produce left and right parallax induced DDMs before transformation into the slope gradient gray scale stereograms shown in Figures 12a and 12b. The parallax induction algorithm is exactly the same as the one used to generate stereograms from DEMs as given by Eyton (1984).

"Contouring the DDM will produce a series of cross-sectional profiles; gray scaling the DDM will produce a display that is reminiscent of the actual view, paintings, and photographs of the various foreground to background planes of terrestrial foothills and mountains when observed from afar."

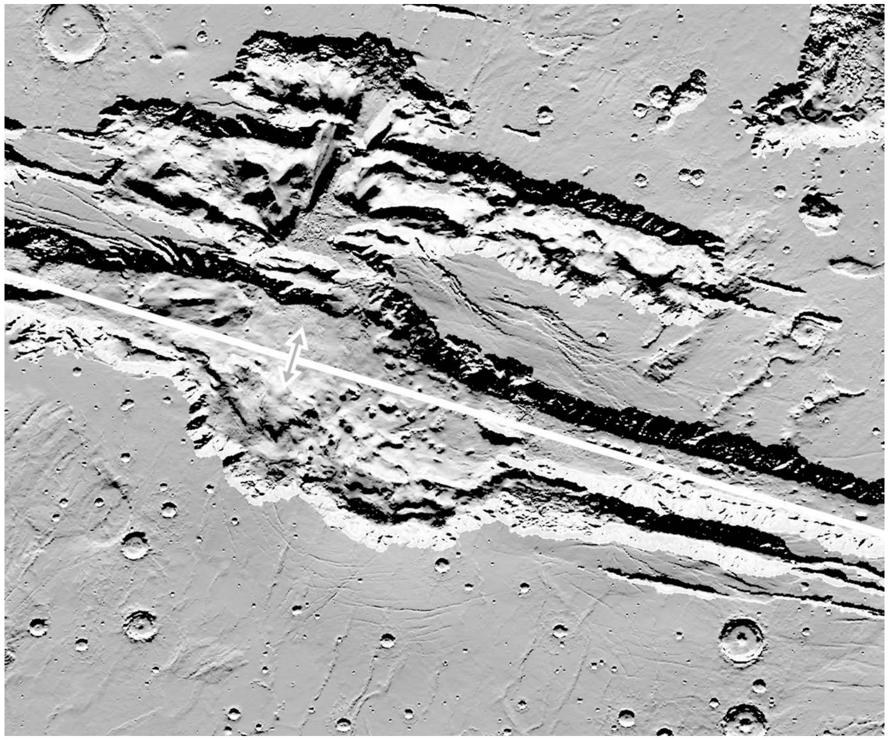
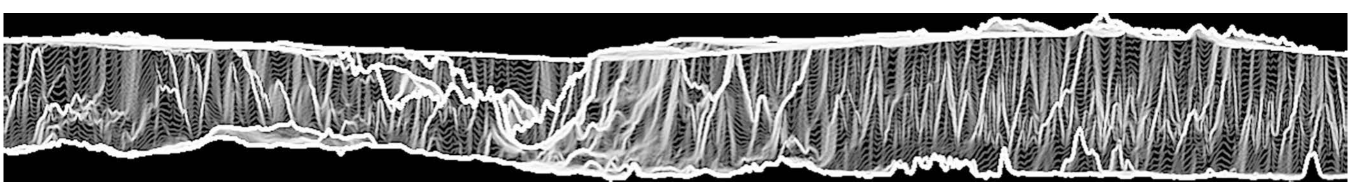
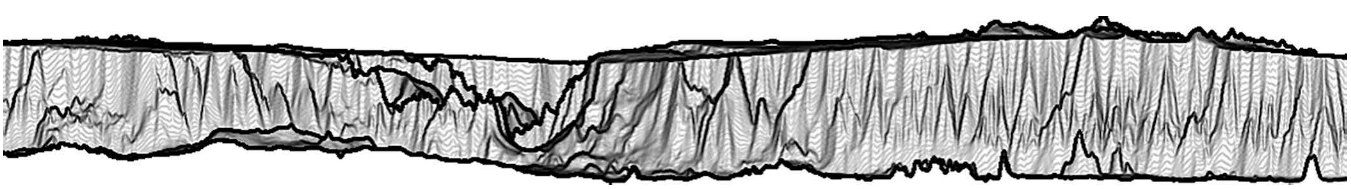


Figure 10. This hillshade image of the central region of Valles Marineris was created from a subset of the Mars 1/64° x 1/64° DEM. The white line bisecting the image into north and south halves corresponds to the location in the DEM where all elevations to the south of the line (along the columns in the DEM) were set to the elevation value occurring at the line. The DDM and resulting images (Figure 11) constructed from this altered DEM shows only detail north of the line. The arrows, located roughly at the center of Mellas Chasma, show the middle location of two additional DDM subsets that were used to create the stereo images shown in Figure 12. The north arrow points to the entrance of Condor Chasma and following the arrow's direction also points to the entrance of Ophir Chasma located immediately north of Condor Chasma. The area covered by this subset is approximately 1093 km (679 mi) west to east and 920 km (572 mi) south to north. Grid cell size at this latitude is about .91 km in longitude and .92 km in latitude. Projection is Equidistant Cylindrical.

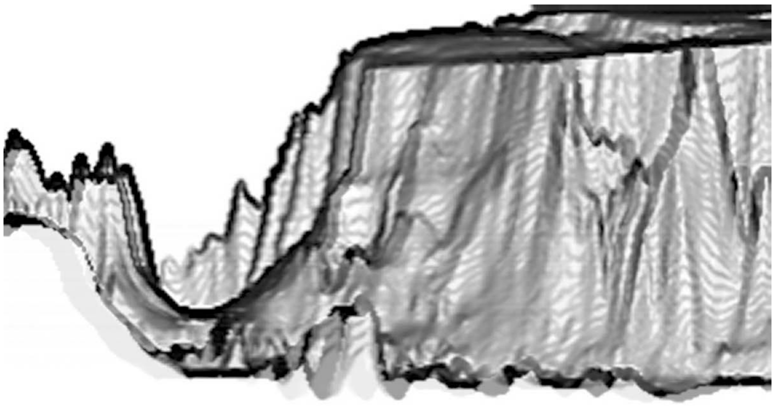


a. Linear gray scale of slope gradients with flat or gentle slopes shown as dark tones and steep slopes shown as light tones.

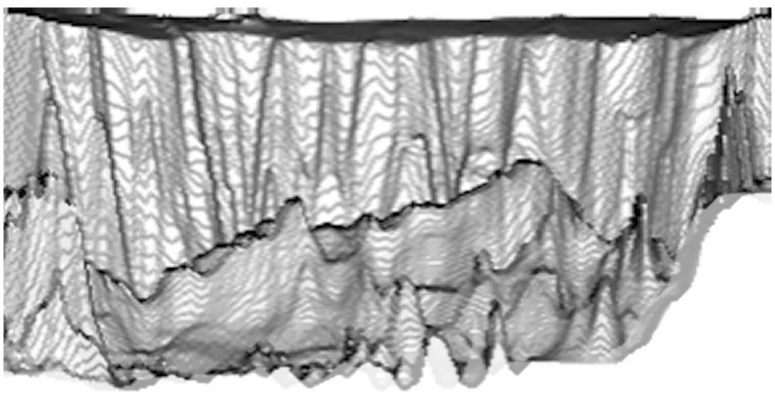


b. Linear gray scale of slope gradients with flat or gentle slopes shown as light tones and steep slopes shown as dark tones.

Figure 11. Images showing gray scales of slope gradients relative to the DDM zero plane.



a. Subset looking north through the opening into Condor Chasma.



b. Subset looking at the south wall of Mellas Chasma

Figure 12. Subsets of the Valles Marineris 1/64° x 1/64° DEM centered on the arrows shown in Figure 10 were converted to DDMs and induced with parallax before creating the left and right perspective slope images in the form of anaglyphs displayed above. Red-cyan glasses with red over the right eye are needed to view these images. (see page 60 for color version)

Discussion

Three new ways to visualize surface geometry using DEMs, with and without thematic overlays, has been presented. Circular gray scaling of a slope azimuth distribution should be of value to investigators interested in examining landform structures in great detail. However, their use as a means for popular depiction of landscapes may be limited because of the harshness of the image brought about by the same overabundance of detail that makes the displays useful for landform analysis. It is possible to mix the plastic-like image of the circular gray scale with the more diffuse-looking image resulting from Lambertian hillshading to produce enhanced hillshaded products. This is a subject of further research.

Tomographic maps have potential as teaching aids, and for providing inexpensive 3D displays that are suitable (requires no viewing aids) for public presentations in information centers. These displays, in both black and white as well as color, require no special equipment to produce but are limited in size (10 in x 12 in) to conventional overhead transparency material that can be printed on inkjet printers. Larger size models could be constructed from transparent films (50 inches wide in long rolls) avail-

"Circular gray scaling of a slope azimuth distribution should be of value to investigators interested in examining landform structures in great detail."

able for large format printers, but the mechanics of separating and stacking large images then becomes the principal problem. Layering the film between thin sheets of clear Plexiglas or acrylic plastic sheets is possible, however the resulting display would be extremely heavy.

"Images from DDMs not only provide a unique horizontal view of land surfaces but also provide displays that might be considered a form of cartographic art."

Images from DDMs not only provide a unique horizontal view of land surfaces but also provide displays that might be considered a form of cartographic art. Their principal advantage is that the same data transformation and mapping manipulations that can be applied to a DEM can also be applied to the extracted DDM. More work needs to be done on the methodology for determining the 'height' or number of rows needed for the DDM. From my limited experience with producing these models, it appears that about ten to twenty percent of the number of grid cells or columns in the row of the initial DEM used as the number of rows to be extracted in the DDM, results in an acceptable DDM display. Application of the DEM to DDM transformation to elevation models generated from LIDAR data may produce a better balance between the horizontal resolution (not accuracy) and the vertical resolution in the DDM with the potential for creating outstanding horizontal displays from vertically gathered data.

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Miscommunicating With Isoline Preference Maps: Design Principles for Thematic Maps

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Gould and White (1968) introduced the measurement and isoline mapping of regional preferences, producing preference or "isoeutope" maps. As cartographers know, the decision to employ isoline mapping as a cartographic display technique is valid insofar as certain assumptions are met, notably the assumption that the variable being mapped reflects an underlying continuum. This assumption is doubtful in the case of a variable such as regional preference insofar as it is based on rankings or ratings of existing regional units such as states for which human cognition is not continuous. The implications of mapping preference with isolines are discussed, particularly with respect to the attitudes the maps reflect and the cognitive responses they elicit in viewers. We argue that isoline mapping of data such as state preferences produces misleading impressions of intraregional variation and is neither necessary nor desirable. Alternative methods for the collection and cartographic display of regional preference data are discussed. Notably, we propose the use of "psuedo-Chernoff" faces as an appropriate technique.

Keywords: Isoline mapping, preference maps, spatial interpolation, cognitive cartography, Chernoff faces

Introduction

In a series of articles published during the 1960s, Gould and White (for example 1968) introduced the cartographic display of people's relative preferences for living in one or another region of a country. This work was subsequently developed most fully in their 1974 book, *Mental Maps*, and its 1986 second edition. Gould and White's cartographic displays provided an early demonstration that subjective, intrapsychic variables (variables that measure thoughts, emotions, attitudes, and so on) could be thematically mapped, much as one maps rainfall, population, or criminal activity.

"Gould and White's cartographic displays provided an early demonstration that subjective, intrapsychic variables . . . could be thematically mapped, much as one maps rainfall, population, or criminal activity."

The notion that subjective variables could be mapped was an important insight. It extended the practice of psychometrics to a geo-referenced context, allowing its cartographic expression. *Psychometrics* is the approximately century-old set of theories and techniques that allow the measurement of subjective variables that do not have direct physical referents; in contrast, *psychophysics*, well explored in cartography for decades (its history is reviewed by Montello, 2002), involves subjective variables that do have physical referents, such as color hue or perceived size (Nunnally and Bernstein, 1994). To many people, it was a revelation that such variables as fear or aesthetic preference could be quantified and mapped, and scientifi-

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cally studied like "objective" variables. In fact, some within geography and cartography apparently still question this (for example, Walmsley and Lewis, 1993).

Early in their research program, Gould and White chose an appealing cartographic technique for displaying their preference data: the *isoline* (or isarithm) map. The isolines in this case represent lines of equal preference or liking for the places they cross; alternatively, they should be interpreted as boundaries between regions of equal preference.[1] Gould and White called them "mental maps," but we believe this term is too general because it implies a mental representation of all beliefs about places (including, for example, spatial layout) rather than a representation specifically of preference. Instead we favor the term "preference maps," or if one wants a precise technical label, we suggest they be called "isoeutope" maps. Our purpose in this paper is to review Gould and White's measurement and isoline mapping of place preferences, review some past criticisms of them, and provide a new critique based particularly on the way they communicate attitudes about preference to viewers of the maps. In the process, we make general observations about isoline mapping, and about the measurement and display of subjective variables like preference. We suggest some alternative mapping methods we think communicate better.

"Early in their research program, Gould and White chose an appealing cartographic technique for displaying their preference data: the isoline *(or isarithm) map."*

Figure 1 depicts an isoeutope map, based on a sample of 55 students from the University of California at Santa Barbara that we surveyed a few years ago (about 85% of them reported having grown up mostly in California). The map in Figure 1 was constructed following the methods typically used by Gould and White. First, respondents were asked to rank order regions in terms of their preferences for living there; respondents were to assume they had no financial, family, or other constraints to consider. In the case of the states of the conterminous United States, one of Gould and White's most studied areas, this results in a 48 x N matrix of numbers, the numerical ranks 1 through 48 for each of N respondents (we originally solicited rankings of all 50 states, Hawaii and Alaska being popular states, but the continuous interpolation involved in isoline mapping does not work with noncontiguous regions). The matrix was reduced to a vector via the multivariate data-reduction technique of principal components analysis (PCA). That is, each state was assigned a mean PCA score reflecting its average consensus preference by the aggregated sample of respondents. (We have found that using mean ranks instead of PCA scores is simpler, at least as theoretically defensible, and produces nearly identical maps—the two are correlated .995 in our data). The PCA scores were transformed and rescaled to range between 0 and 100, the most preferred states being assigned the highest values. Each state's mean rescaled PCA score was assigned to a point location within that state (we used spatial centroids). This spatial distribution of points was then subjected to cartographic interpolation to produce smooth and continuous isoeutopes connecting places of equal preference. This interpolation can be done formally or informally—we used inverse-distance weighted interpolation. On the resulting map, ridges of highly desirable areas and valleys of undesirable areas are evident.

"We believe that isoline mapping is a poor choice for this type of data primarily because it produces misleadin impressions of intraregional preference variations among viewers . . ."

We believe that isoline mapping is a poor choice for this type of data primarily because it produces misleading impressions of intraregional preference variations among viewers, especially relatively naive viewers. More than once, while gazing at one of Gould and White's maps, students in our classes have remarked that, for example, respondents obviously preferred coastal California to the Central Valley and other points east, or respondents liked the Denver area more than the mountains to the west. Even though these students were told the maps were based on single