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Analysis of Regional Slope Characteristics on Venus and Earth

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Regional slope values for earth and Venus are calculated for each 3° × 3° region of topography, and the global characteristics of these magnitudes are examined and compared. The effects on terrestrial regional slope due to ocean loading are treated by approximating the component of seafloor depth due to the weight of the overlying water column and removing this component from the ocean topography. Although regional slopes on Venus and earth span the same range, 0.0°–2.4° (±0.07°), the slope frequency distributions for the two planets differ significantly. The most abundant regional slope values for the terrestrial cases (earth and unloaded earth) are 0.0° and reflect the presence of vast plains associated with the continental interiors and ocean abyssal plains. In contrast, Venus exhibits a peak in slope frequency at approximately 0.09°, perhaps indicating less effective planation processes in the absence of a hydrosphere. Surfaces with regional slope values of 0.07°–0.24° are substantially more common on Venus than on earth. Slopes in this range are associated with discrete features in the lowland and upland rolling plains provinces of Venus and may be indicative of a geologic process that is not commonly observed on earth. Only 14 ± 1% of all Venus surfaces have regional slopes above 0.24°, compared to 26 ± 1% for earth. When mean regional slope is calculated as a function of elevation, a distinctive positive correlation is expressed on Venus. In contrast, the terrestrial cases exhibit a complex relationship marked by four modes related to the presence on earth of an active hydrosphere-driven weathering regime, a distinctive crustal dichotomy, and plate tectonics. The distinctions in the regional slope characteristics between Venus and earth point to a simpler, less diversified geology on Venus.

INTRODUCTION

Regional slope is a scale-dependent parameter that describes the planar surface gradient averaged over a relatively broad area of topography. As such, it has a fundamental relevance to the geological evolution of a planetary surface: it is controlled by the interaction of those processes which tend to increase or reduce surface relief (e.g., tectonism, volcanism, impact cratering, weathering, viscous relaxation) and, in turn, exerts control on the erosion, transportation, and deposition of surface materials.

The Pioneer Venus (PV) radar experiment provided over 200,000 altimetry measurements with a vertical accuracy of 200 m [*Pettengill et al.*, 1980], covering over 93% of the surface of Venus. These data have been compiled into a 1° × 1° global topographic data set for surfaces between 65°S and 78°N latitude. *Masursky et al.*, [1980] used these data to compare the global hypsometry of Venus and earth and to classify global physiographic provinces on Venus as follows: lowlands (regions with elevations less than the Venus datum of 6051.0 km, forming 27% of the surface), upland rolling plains (Venus datum to +2.0 km, comprising 65% of the surface), and highlands (regions above +2 km, constituting 8% of the surface). The hypsometric curves, the global topographic provinces, and features within the provinces have provided a basis for the analysis of the geological processes shaping the surface of Venus [*Pettengill et al.*, 1980; *Masursky et al.*, 1980; *Arvidson and Davies*, 1981; *Head et al.*, 1981; *Phillips et al.*, 1981; *Brass and Harrison*, 1982; *Solomon and Head*, 1982; *McGill et al.*, 1983].

Here we first analyze the altitude frequency distribution for Venus (derived from the PV data discussed above) and earth (derived from the Rand 1° global data of equivalent resolution). Using the method outlined in the appendix, we calculate the regional slope values corresponding to the 3° × 3° region centered about each elevation measurement in the Venus and earth topography (Figure 1). The standard error of individual regional slope values is calculated to be 0.035°, yielding a 0.95 confidence interval of ±0.07° about each measurement. We describe the range and frequency distribution of slopes on Venus and earth, analyze trends in mean regional slope versus elevation, and examine the effects on terrestrial regional slope resulting from the removal of the ocean load from seafloor topography. Finally, we discuss the similarities and differences of the two planets in terms of these parameters. In a separate paper [*Sharpton and Head*, 1984] we present the regional slope characteristics for major topography features discernible on Venus at PV resolution and compare these with slope features associated with terrestrial landforms.

OBSERVATIONS

Altitude-Frequency Distribution

On the basis of Pioneer Venus altimetry data, elevations on Venus range from 6049.0 to 6062.1 km, over 13 km. For earth the range of elevations is 19.7 km. When elevations are averaged over regions comparable to the PV baseline (approximately 100 × 100 km), the global range is reduced to 15.4 km [*Head et al.*, 1981]. Although the range of elevations on Venus is smaller than that of earth, the full range of Venus has probably not been sampled because of the large average footprint size. This, however, would not contribute to the differences in regional slope properties of Venus and earth discussed below because both planetary data sets are of equivalent resolution.

The elevation frequency distributions for Venus and earth are shown in Figure 2. Comparisons of the topography of Venus and earth must consider the influence of the load of terrestrial oceans on the lithosphere, and the temperature differences between Venus and earth, both of which relate to the topographic evolution of the oceanic lithosphere thermal boundary layer [*Arvidson and Davies*, 1981; *Head et al.*, 1981].

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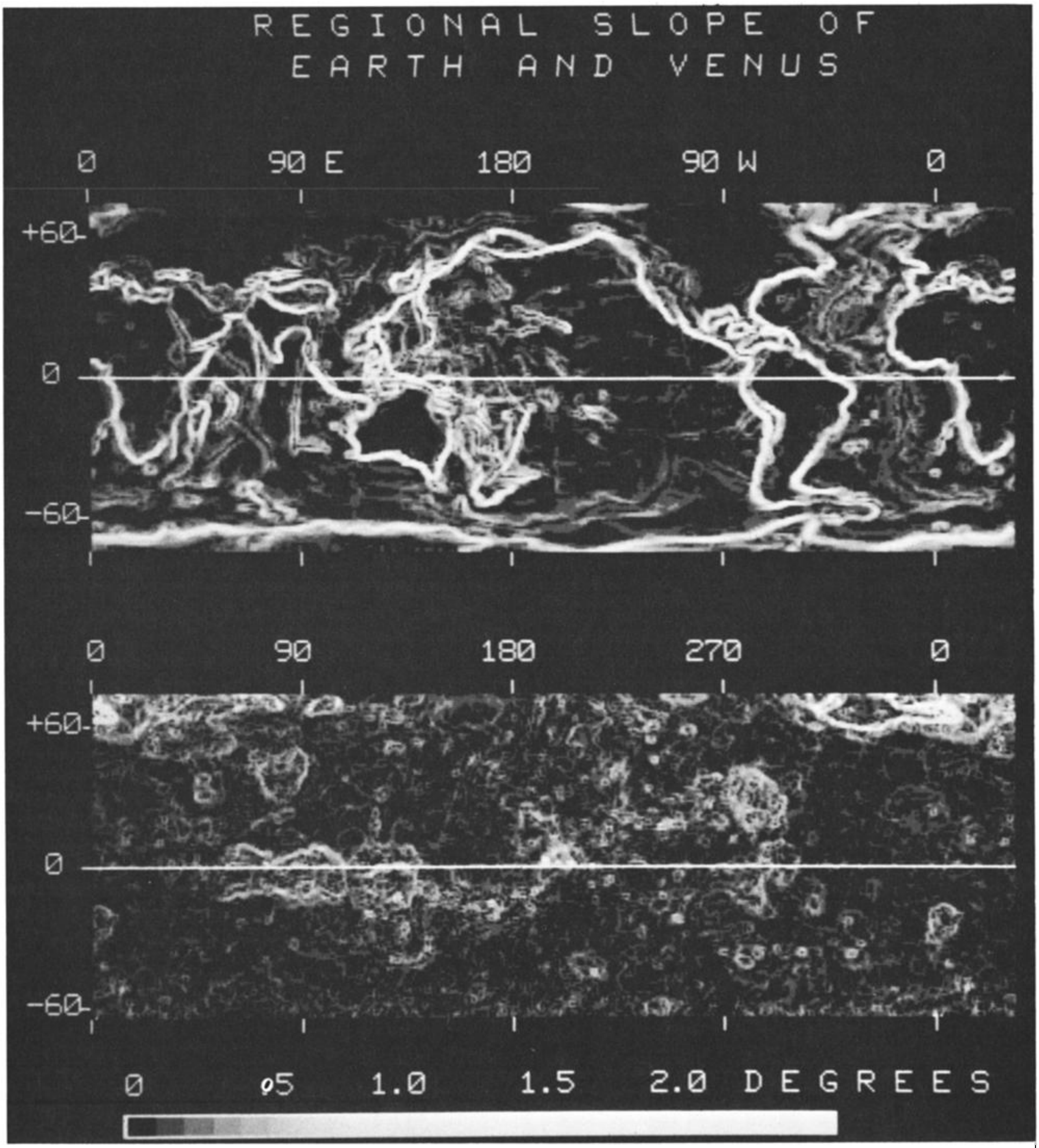

Fig. 1. Regional slope maps of earth (top) and Venus produced by the method discussed in the appendix. Regional slope values increase with brightness in 0.1° increments; the range of values extends to 2.4° on both planets.

Although we correct only for the ocean load, the effects of unloading the seafloor and increasing surface temperature to correspond to Venus conditions are similar [*Arvidson and Davies*, 1981]. The distinct contrast between the earth's bimodal distribution and the strong unimodal distribution of Venus is obvious in Figure 2. Unloading of the earth's oceans shifts seafloor topography to higher elevations, but the characteristic bimodal distribution is retained.

Slope-Frequency Distribution

The relationship between regional slope and percent surface area for earth, unloaded earth, and Venus is shown by Figure 3. The general shape of these curves can be described by a function relating regional slope and percent area of the form $A = kS^{\alpha}$, where A is percent total surface area (expressed as a fraction), S is regional slope in degrees, and k and α are constants. Table 1 gives the values of these constants and the correlation coefficient associated with the least square fits as well as the mean, median, and range for each slope frequency curve shown in Figure 3. When calculated over a regional baseline of about 300 km, surface slopes range from 0° to 2.4° (±0.07°) for both earth and Venus. The mean Venus slope (0.14° ± 0.001°) is lower than that of the earth (0.21° ± 0.001°) but close to the mean unloaded earth slope (0.16° ± 0.001°).

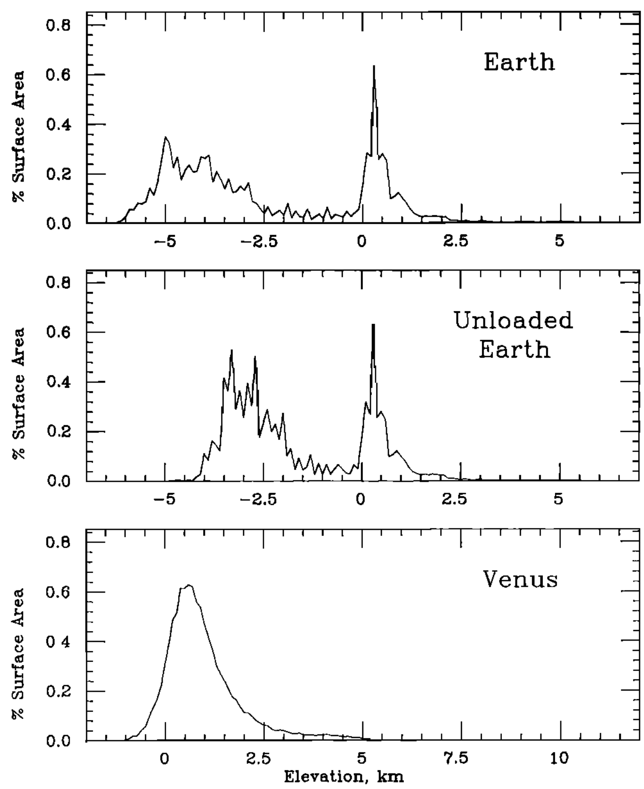

Fig. 2. Differential hypsograms for the three topographic data sets used in this analysis. All three data sets are of equivalent spatial and vertical resolution. Each plot illustrates the frequency of occurrence of surface elevations grouped in 100-m elevation increments. For both terrestrial cases, 0.0-km elevation refers to sea level; for Venus, elevations are referenced to a planetary radius of 6051.0 km.

The frequency distribution of regional slopes on Venus and earth are broadly similar, but they show wide variation in detail.

The modal regional slope value for the earth curve is 0.0°, which represents about 26% of the planet's surface area. For Venus the mode occurs between 0.07° and 0.1° and represents about 23% of the surface, whereas only about 20% of the Venusian surface falls in the 0.0°–0.07° range. These observations indicate a global deficiency in regionally flat surfaces on Venus compared to earth. On the other hand, slopes between 0.07° and 0.24° are substantially more abundant on Venus than on earth: about 66% of the surface of Venus and approximately 48% of the terrestrial surface have regional slopes falling in this range. In addition, only 14 ± 1% of the Venusian surface has slopes greater than 0.24°, whereas 26 ± 1% of the earth's surface are in this range.

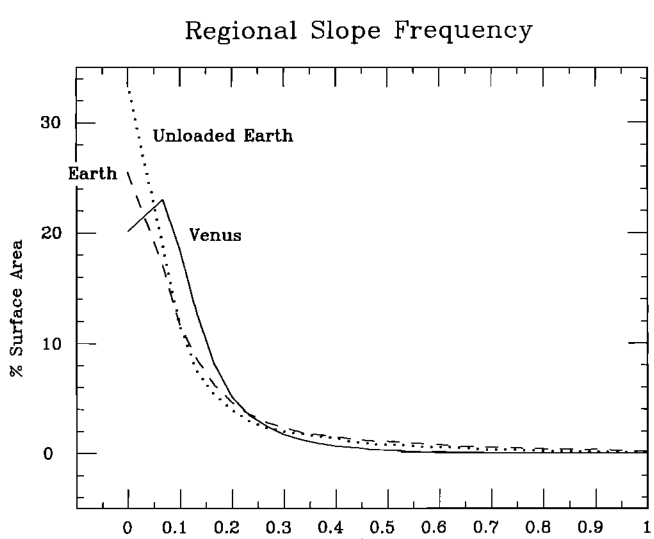

Fig. 3. Regional slope frequency diagram for the three topographic data sets used in this analysis. Each plot illustrates the frequency of occurrence of regional slopes with data grouped such that the first interval, plotted at 0.0°, includes regional slopes in the range of 0.0°–0.07°; all other intervals are 0.035° wide and are plotted at the minimum slope value. See text and appendix for details.

TABLE 1. Regional Slope Frequency Distribution Statistics

	k	α	R^2	Mode	Mean	Median	Range
Earth	$10^{-3.11}$	−2.87	0.88	0.00°	0.21°	0.12°	0.0°–2.4°
Unloaded Earth	$10^{-3.37}$	−3.01	0.89	0.00°	0.16°	0.08°	0.0°–2.2°
Venus	$10^{-3.81}$	−3.32	0.90	0.09°	0.14°	0.12°	0.0°–2.4°

The k, α, and R^2 refer to the constant of proportionality, the exponent, and the correlation coefficient, respectively, of the least squares exponential regression line fitting each regional slope frequency relationship. The mode, mean, median, and range refer to the statistics of the actual data as they are presented in Figure 3. Total number of data points in each population is 49,320.

The slope characteristics of the unloaded earth curve are even less like those of Venus. About 33 ± 1% of unloaded earth's surface has approximately 0.0° slope, exceeding the Venus value by about 13%. In the slope range between 0.07° and 0.24° there is little variation between the two terrestrial curves: Venus has a significantly larger percentage (66 ± 1%) of its total surface within this interval than does the unloaded earth (47 ± 1%). It is only for slopes greater than about 0.3° that the differences between the Venus and earth distributions are lessened slightly from 8 ± 1% (loaded) to 6 ± 1% (unloaded). In order to interpret the geological significance of these data, information on the relationship of slopes and elevations is required so that slopes can be related to geologic and geomorphologic provinces.

Correlation of Mean Slope and Elevation

The relation between regional slope values and elevations can be established by calculating the mean slope value for each 100-m elevation interval and displaying this together with the standard deviation associated with each mean slope value. On Venus there is a distinct positive correlation between mean slope and altitude (Figure 4). Lowest elevations (−2.0 to −1.5 km) are characterized by relatively high mean slopes, which are strongly influenced by the presence of linear, steep-sided troughs (chasmata) in and around Aphrodite Terra and Beta Regio [*Schaber*, 1982; *Campbell et al.*, 1984]. This zone is followed by an elevation range characterized by constant regional slope (about 0.1°) extending to elevations of approximately 0.3 km. From 0.3 to 3.5 km the regional slope increases consistently with elevation. Above 3.5 km, mean regional slope varies widely with elevation, but a distinct depression in slope is apparent between 3.5 and 5.0 km corresponding to high plateau regions within western Aphrodite Terra, Lakshmi Planum, and eastern Ishtar Terra. For elevations above 4.5 km the mean slopes are extremely high and highly variable, reflecting the mountainous terrain characteristic of these elevations. Standard deviations of the mean slope values are only slightly lower than the slope value itself, suggesting

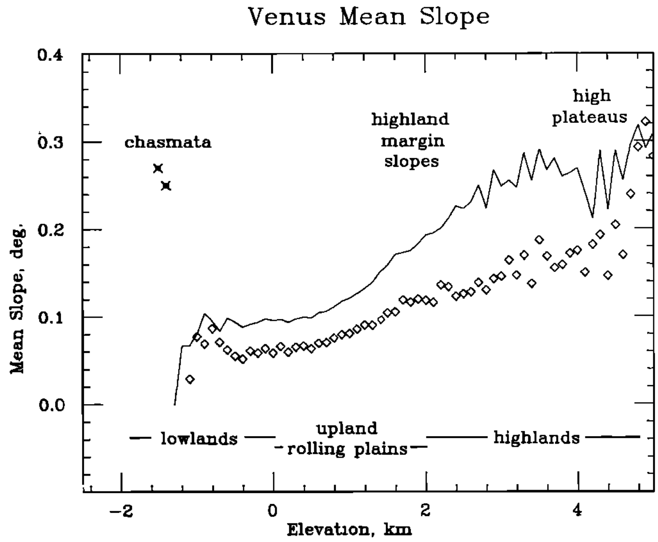

Fig. 4. Mean regional slope as a function of elevation for Venus (solid line). Diamonds indicate the standard deviation associated with the mean slope for each elevation interval. "Sputniks" denote infrequent occurrences of high mean slope at very low elevations. Labels give the approximate location of terrain features which may influence the mean slope values. Topographic province ranges [*Masursky et al.*, 1980] are also denoted. Elevations are referenced to the planetary radius 6051.0 km. Mean regional slope values calculated for surfaces between −1.0 and 4.0 km elevation have 0.95 confidence levels of less than 0.01°.

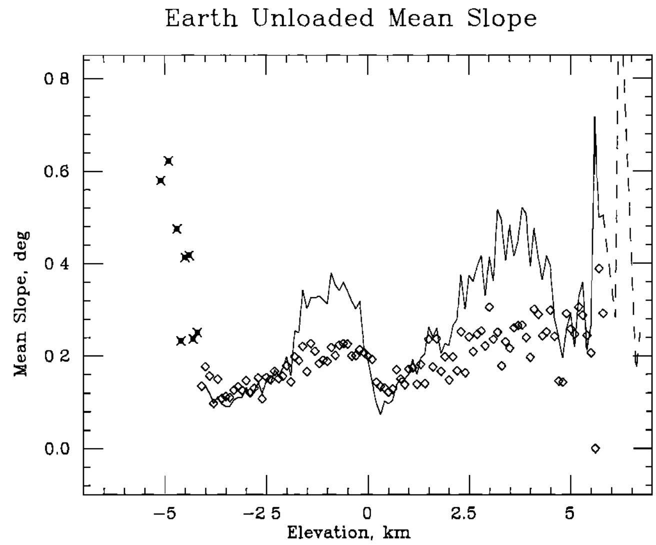

Fig. 6. Mean regional slope as a function of elevation for the unloaded earth (solid line). Symbols are the same as in Figure 4. The technique used to produce the unloaded earth topography is given in the appendix.

that the terrain occurring at a given elevation is relatively variable in slope magnitude. Furthermore, the standard deviations increase systematically with elevation and equal or exceed the mean slope values above about 4.5 km.

The specific boundaries of the major physiographic provinces of Venus [*Masursky et al.*, 1980] do not appear to be marked by major or abrupt changes in mean slope. The lowlands and the lower part of the upland rolling plains (−1.5 to +0.3 km) are characterized by constant mean slopes of approximately 1° and low standard deviations. Furthermore, the transition between this elevation interval and the broad interval marked by increasing slope values with elevation (0.3–3.5 km) is gradational with regard to mean slope and standard deviation. Thus no distinct boundary between the lowlands and the upland rolling plains is discernible, nor is there any discrete change in mean slope properties within these provinces to indicate a geological basis for their separation. Between approximately 0.3 and 3.5 km, regional slope increases systematically with elevation. For discussion we divide this elevation interval into three zones on the basis of inflections in mean slope and standard deviation: a lower zone from about 0.3 to 1.3 km, a middle zone from 1.3 to 2.4 km, and an upper zone from 2.4 to 3.5 km. Analysis of the areal distribution of regional slope features [*Sharpton and Head*, 1984] reveals that the lowlands and upland rolling plains provinces contain two types of slope features (Figure 1): (1) small (less than about 7° wide) regions of 0.0°–0.1° slope, separated by (2) narrow linear, arcuate or circular features with regional slope values in the range of 0.1°–0.2°, whose frequency of occurrence increases with elevation. Thus the increase in mean slope within the lower zone (0.3–1.3 km) in Figure 4 appears to reflect the increased abundance of this 0.1°–0.2° slope component as elevation increases (Figure 2) rather than a systematic steepening of slope with elevation. The margins of the major highland regions are marked by distinct high regional slope features in the range of 0.1°–0.4° [*Sharpton and Head*, 1984]. The incorporation of these highland margin slopes (Figure 2) appears to be responsible for the middle zone (1.3–2.4 km; Figure 4). The upper zone (2.4–3.5 km) is marked by larger variations in mean slope and standard deviation than the lower and middle zones. This is the transition zone between the steep but variable highland margins and the highland interiors (characterized by interior rugged terrain and high plateaus). The occurrence of these diverse terrain components appears to explain the large variation in mean slope and high dispersion characteristic of this elevation range. The broad elevation

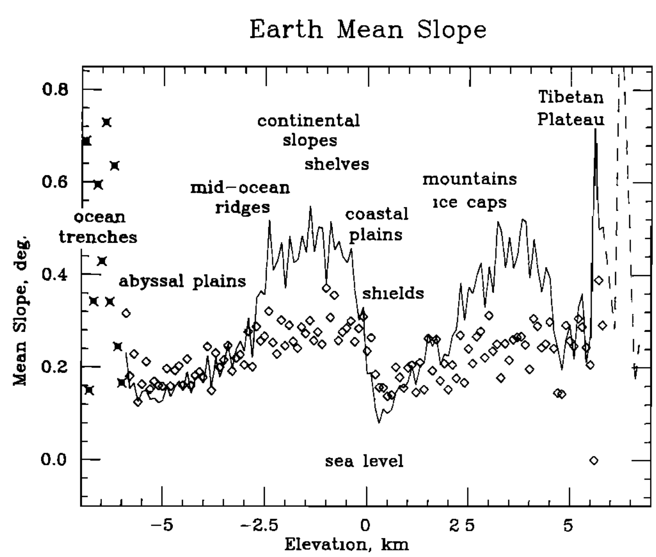

Fig. 5. Mean regional slope as a function of elevation for earth (solid line). Diamonds are standard deviations. "Sputniks" signify small proportion of deep ocean surfaces associated primarily with ocean trenches. Dashed line indicates localized terrain associated with the Tibetan Plateau and Himalayan Front. Labels denote approximate elevations of major terrain features influencing mean slope values. Mean regional slope values calculated for surfaces between −4.0 and 2.5 km elevation have 0.95 confidence levels of less than 0.01°.

range (approximately 2 km) of highland margin slopes is partly because the margins do not parallel elevation contours and partly because the steeply sloping margins of Beta Regio, Aphrodite Terra, and Ishtar Terra do not occur at the same elevation interval. The highland margins, therefore, do not appear to be an expression of an ancient ocean on Venus [*Donahue*, 1982] unless considerable surface deformation has occurred subsequently.

The relationship of mean slope and elevation on earth appears to be considerably different and more complex (Figure 5) than is the case on Venus (Figure 4). The earth shows four specific modes. At the lowermost elevations, mean slope is high, but highly variable, representing the topography characteristic of oceanic trenches and their surroundings. Mean slope decreases with increasing elevation in the ocean basins until a trough is reached at about −5 km, signifying the location of the regions of flat abyssal plains. Mean slope shows a steady increase with elevation between −5.0 and −2.5 km, representing the thermal boundary layer topography associated with oceanic ridges and rises. Between −2.5 and sea level occurs a broad peak representing the relatively steep slopes of the continental slope regions and the flanks of numerous seamounts and islands. The major trough associated with sea level represents the continental shelves (below sea level) and continental coastal plains (above sea level). Above about 0.5 km mean slope begins a steady increase through old mountain belts and continental plateaus (0.5–0.8 km) toward the high plateaus, young mountain belts and ice caps which form the third major peak. A final trough is encountered at +5 km before the slope increases again in the regions of highest topography on earth associated with the Himalayan Front. This trough is primarily an expression of the relatively flat nature of the Tibetan Plateau when examined at this scale.

Thus the earth's polymodal distribution of mean regional slope as a function of elevation differs markedly from the generally positive increase of mean slope with elevation for Venus. On earth the different parts of the distribution owe their major characteristics to specific processes or factors. The lowermost peak is related to tectonic subduction zones. The systematic increase in mean regional slope from about −5.0 to −2.5 km is due predominantly to the characteristics of the cooling thermal boundary layer of the oceanic lithosphere and (to a lesser degree) the mantling of this seafloor topography by pelagic sediments. The steep slopes between −2.5 km and sea level are due primarily to the density and thickness differences between continental and oceanic crust and are accentuated by the differences between active and passive continental margins and age of passive margins (thermal structure; erosion and sedimentation). The areas of high slopes above sea level are primarily related to mountain and plateau topography associated with convergent plate boundaries. The areas of lowest slopes (centered at −5 km and sea level) are associated with atmospheric and hydrospheric erosion and depositional processes (continental shields and plains, continental shelves, and abyssal plains).

Mean regional slope as a function of elevation for the unloaded earth is shown in Figure 6. The major characteristics of the distribution remain the same. However, slopes below sea level are shifted to higher elevations, the "abyssal plains" trough is broadened as unloaded oceanic lithosphere is decreased in slope, and there is a corresponding decrease in the amplitude of the continental slope peak as elevation differences between continental shelves and adjacent ocean floor decrease.

DISCUSSION

Although there are major differences between the shapes of the mean slope versus elevation plots for Venus and earth (Figures 4, 5, and 6), there are also some similarities. The trough in mean slope values surrounding sea level is largely due to the erosional and depositional influence of water. If water erosion and sea level were absent from the earth environment, slopes in this elevation interval would not be as subdued and the trough in mean slope values would be correspondingly less deep, if it existed at all. Second, removal of the oceanic load on the lithosphere (Figure 6) decreases the slopes associated with the thermal boundary layer ocean rise topography and those associated with the continental slopes. Addition of the temperature difference factor would enhance these changes. These major influences would tend to modify the earth mean regional slope diagram (Figure 5) to appear more similar to the Venus mean regional slope diagram (Figure 4).

The correlation of mean slope and elevation provides the data necessary to analyze the slope frequency distribution for Venus and earth (Figure 3). The abundance of very low slopes on earth relative to Venus can be attributed to the presence on earth of oceanic abyssal plains, continental interiors (shields and platform sediments), shelves, and coastal plains. Areas of comparable smoothness are not statistically abundant on Venus but are most common in the lowlands and lower upland rolling plains provinces. There is an abundance of intermediate value (0.07°–0.24°) slopes on Venus relative to earth. Slopes in this interval are typical of the upland rolling plains, and as this province comprises 65% of the surface of Venus, the majority of these slope values are associated with this province. On earth, oceanic ridges and rises and a range of continental topography fall in this slope interval [*Sharpton and Head*, 1984] but do not make up as significant a portion of the surface of the planet. The abundance of steeper slopes on earth relative to Venus is caused by the higher percentage of earth "highlands" (continents), the large number of relatively recent mountain ranges, the occurrence of trenches, and the presence of continental slopes surrounding terrestrial continental regions.

CONCLUSIONS

The range of regional slopes (calculated over 3° × 3° areas) on Venus and earth is essentially the same, although the frequency distribution is quite different for the two planets. On Venus the model slope is distinctly higher than earth's, indicating an abundance on earth of regionally flat surfaces relative to Venus. While Venus displays a relative paucity of regionally flat surfaces, it has an abundance of surfaces with intermediate slopes (approximately 0.07°–0.24°). Relatively steep regional slopes (above approximately 0.24°) occur more frequently on earth than on Venus. Removal of the ocean load from the seafloor does not dramatically alter these major trends in slope frequency distribution. The mean regional slope of Venus increases systematically with elevation, while earth's is distinctly polymodal, even when taking into account temperature and lithospheric load differences between Venus and earth.

We conclude that Venus and earth show fundamental differences in terms of the distribution of large-scale regional slopes. We interpret these differences to be due to the interaction of at least three factors:

Atmosphere/hydrosphere. The earth's atmosphere and hydrosphere and their role in erosional and depositional processes are clearly a fundamental factor in the production of the abundance of very low slopes on earth relative to Venus. In addition, the localization of sea level at a specific elevation range is largely responsible for one of the major troughs in the earth mean slope/elevation distribution. Implications for Venus are that erosion and sedimentation are not so efficient at producing and maintaining low slopes as they are on earth. Furthermore, if Venus once had an ocean of global proportions [*Donahue*, 1982], it was not as widespread or influential on topographic slopes as is earth's, or, alternatively, subsequent events have obscured its effects.

Lateral crustal density and thickness differences. Density and thickness differences between continental and oceanic crust on earth are responsible in part for the bimodality of earth's hypsogram (Figure 2) and for the peak in the mean regional slope/elevation distribution (Figure 5) represented by continental slopes. On Venus a unimodal hypsometric curve (Figure 2) and the lack of a strong peak in the mean slope/elevation profile could be interpreted as evidence against distinct lateral variations in crustal properties. We feel that this conclusion is premature, however, because the abundance of highlands on Venus is less than one third that of continents on earth [*Morgan and Phillips*, 1983; *Phillips and Malin*, 1983; *Phillips et al.*, 1981] and crustal thickness variations could offset the isostatic height differences expected from lateral density variations (high-density crust could be proportionally thicker than low-density crust). In addition, viscous deformation may smooth out isostatic height variations on Venus [*Weertmann*, 1979; *Solomon et al.*, 1982]. Major Venus highland regions are surrounded by continuous narrow zones of increased regional slope comparable to, but lower in magnitude than, terrestrial continental slopes [*Sharpton and Head*, 1984]. Thus density and thickness differences between Venus highlands crust and surrounding regions cannot be ruled out at the present time on the basis of these data.

Tectonic regime. Portions of the terrestrial slope characteristics are clearly but not uniquely related to earth plate tectonics (e.g., low slopes related to old oceanic lithosphere, increasing slopes as a function of elevation relative to thermal boundary layer topography, and steep slopes related to subduction zones and convergent continent-continent plate boundaries). Because of the nonuniqueness of the correlations an assessment of the presence or absence of plate tectonics on Venus cannot be made on the basis of these data alone. However, Venus slope characteristics suggest that the Venus lowlands and rolling uplands differ from plate tectonic dominated oceanic lithosphere on earth. The much higher frequency of intermediate level slopes on Venus suggests that broad expanses of older, relatively flatter oceanic type lithosphere would not be as abundant as on earth, if present at all. A decrease in plate size and an increase in the number of plates could cause an increased abundance of intermediate slopes such as that observed on Venus. Thus the regional slope relationships presented here demonstrate that the Venus lowlands and upland rolling plains are different from the earth's ocean floor but do not establish the tectonic origin of these differences. The surface distribution of regional sloes on Venus (Figure 1), however, reveals that features with intermediate slope values (0.1°–0.2°) form a systematic arrangement throughout most of the lowlands and upland rolling plains, dividing these provinces into small, flat-lying regions typically less than about 7° wide. These features appear to account for the relative abundance of regional slopes in this range on Venus compared to earth. Thus these intermediate Venus slopes do not appear to be expressions of the boundaries of smaller, more numerous plates unless these plates are constrained to be only a few hundred kilometers wide.

Finally, we note that Venus shows a relatively systematic increase in mean regional slope with elevation (Figure 4) while the mean slope/elevation relationship for earth (Figure 5) is punctuated in several places. This difference suggests that Venus is characterized by a simpler and less diverse interplay of formation and destructional processes than is earth. The paucity of flat regional surfaces on Venus relative to earth appears to indicate that degradation and aggradation processes (e.g., erosion, deposition, volcanic infilling) are relatively ineffective on Venus. In addition, the abundance of regional slopes on Venus between approximately 0.07° and 0.24° implies either that surface processes are not effective at reducing slopes beyond this range or that some geological process operates on Venus to preferentially generate landforms with regional slope characteristics in this range.

APPENDIX

Data. The global terrestrial data set used in this regional slope analysis was the revised Scripps Institute 1° tabulation [*Gates and Nelson*, 1975*a*, *b*]. These data form a digital grid of elevation values averaged over each 1° latitude by 1° longitude cell (1°/pixel). The Pioneer Venus altimetry measurements were compiled into a comparable 1° grid using spatial averaging and interpolation techniques similar to those discussed by *Arvidson et al.* [1982]. The Venus topographic coverage extends from 62°S to 75°N, and only earth topography within this range was considered. As Venus and earth are comparable in size ($R_V = 0.95\ R_E$), elevations are averaged over virtually equivalent surface areas for both topographic grids; thus variations in slope characteristics between the two planets should not be due to scale variations.

The "unloaded earth" data represent the effects on elevation and regional slope the seafloor would undergo if the load of the overlying water column were removed and this topography were allowed to isostatically reequilibrate. To approximate the unloaded earth topography, a correction, relating unloaded seafloor depths d_u to loaded depths d_l, was applied to the earth topography. The correction factor used ($d_u = 0.7d_l$) is based on relationships developed by *Parsons and Sclater* [1977] and further discussed by *Head et al.* [1981].

As the Scripps data were compiled from visual estimates of various charts and topographic maps, the errors associated with the elevation values for earth depend upon the availability of terrain data and the complexity of the topography within each 1° cell. However, no error estimates accompany these data, and none have been published subsequently. Thus, in order to evaluate data accuracy we compared these data with 1° regions covered by various bathymetry charts of the seafloor [*Chase et al.*, 1970; *Mammerickx et al.*, 1975] and the 30-s digital data for the western United States. Data for the continental regions typically agreed within a few tens of meters with regions of high and variable relief having differences of up to 300 m. Precision of ocean measurements is variable and reflects the uneven topographic coverage of the deep oceans. Most areas of poor topographic coverage, however, are abyssal plains regions of low relief, and thus interpolation across these regions probably does not introduce serious errors in the average measurements. We found good agreement between the Scripps digital data and the bathymetry charts; differences were typically less than 100 m. Thus, for the earth topography overall a reasonable estimate of the standard error appears to be 100 m.

The overall standard error associated with PV altimetry is 200 m [*Pettengill et al.*, 1980]. This error, however, is a function of (among other things) elevation and surface roughness. For low elevations that are relatively smooth (such as the lowlands and the lower portions of the upland rolling plains) the standard error is about 50 m (P. Ford, personal communication, 1984). In addition, averaging several individual measurements within a cell also reduces the standard error in the 1° topographic grid. We thus consider 100 m to be a representative error estimate associated with the Venus 1° topography.

Method. To derive the regional slope values, a spatial filtering algorithm was applied to the topography data sets of Venus and earth. For this analysis the filter window was set at 3 × 3 pixels to discriminate slope variations over 3° × 3° regions. The nine altimetry data points falling within the filter window were used to calculate a best fit plane by means of the least squares regression criterion

$$\sum (z_i - \bar{z}_i)^2 \quad \text{is minimized} \tag{1}$$

where z_i is the elevation value at each location i and $\bar{z}_i$ is the calculated elevation of the plane at that point. Thus

$$\bar{z}_i = a_0 + a_1 X_i + a_2 Y_i \tag{2}$$

Equation (1) can be expressed as

$$f(a_0, a_1, a_2) = \sum [z - (a_0 + a_1 X + a_2 Y)]^2 \tag{3}$$

To satisfy (1), the minimum of (3) is found by partial differentiation to generate the normal equations here expressed in matrix form as

$$\begin{bmatrix} n & \sum X_i & \sum X_i^2 \\ \sum X_i & \sum X_i^2 & \sum X_i Y_i \\ \sum Y_i & \sum X_i Y_i & \sum Y_i^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum z_i \\ \sum X_i z_i \\ \sum Y_i z_i \end{bmatrix} \tag{4}$$

The system of equations is solved for a_0, a_1, and a_2, the partial regression coefficients of (2). The maximum slope of this plane (in degrees) is given by

$$\nabla = \tan^{-1}(a_1^2 + a_2^2)^{1/2} \tag{5}$$

This value was stored in an output file at a location corresponding to the topography data point currently at the center of the filter window. The filter window was advanced 1° and the procedure repeated until all data within each topography array were processed to generate the regional slope relationships used in this analysis.

Error analysis. The uncertainties in the partial regression coefficients a_j $(j = 1, 2)$, arising from random, independent errors in the elevation measurements, can be evaluated by combining the uncertainties of the individual data points σ_i with the effect each data point has on the determination of the coefficients $\partial a_j/\partial z_i$

$$\sigma_{a_j}^2 = \sum [\sigma_i^2(\partial a_j/\partial z_i)^2] \tag{6}$$

summing over $i = 1, 9$.

The derivative can be evaluated [*Bevington*, 1969] as

$$\frac{\partial a_j}{\partial z_i} = \sum_{k=1}^{n} \left[\frac{1}{s_j}\frac{1}{s_k} r_{jk}^{-1}\left(\frac{\partial s_{kz}^2}{\partial z_i}\right)\right] \tag{7}$$

where n is the number of variable coefficients, r_{jk} is the jkth element of the matrix r of partial correlation coefficients, s_{kz}^2 and s_j are the sample covariance and variance terms given by

$$s_{kz}^2 = \{1/(N-1) \sum [1/\sigma_i^2(X_j - \bar{X}_j)(z_j - \bar{z}_j)\} \cdot [(1/N) \sum 1/\sigma_i^2]^{-1} \tag{8}$$

$$s_j^2 = \{1/(N-1) \sum [1/\sigma_i^2(X_j - \bar{X}_j)^2]\}[(1/N) \sum 1/\sigma_i^2]^{-1} \tag{9}$$

and

$$\frac{\partial s_{kz}}{\partial z_i} = \{1/(N-1) \sum [1/\sigma_i^2(X_k - \bar{X}_k)]\}[(1/N) \sum 1/\sigma_i^2]^{-1} \tag{10}$$

The uncertainty in the coefficient a_j is obtained by combining (6) and (7)

$$\sigma_{a_j}^2 = [1/(N-1)(1/s_j^2) r_{jj}^{-1}][(1/N) \sum 1/\sigma_i^2]^{-1} \tag{11}$$

For the planar case with two variable coefficients, r_{jj} is an element within the 2 × 2 matrix of partial correlation coefficients. Upon inversion and simplification,

$$r_{jj}^{-1} = \frac{s_1^2 s_2^2}{1 - (s_{12}^2)^2} \tag{12}$$

The variance of the slope of the regression plane σ_∇^2 is calculated by differentiating the argument of (5) with respect to a_1, a_2:

$$\frac{\partial \nabla}{\partial a_j} = \frac{a_j}{(a_1^2 + a_2^2)^{1/2}} \tag{13}$$

Thus by (6) the variance of the planar slope as a function of the variances of the partial regression coefficients a_1, a_2 is given by

$$\sigma_\nabla^2 = \frac{a_1^2 \sigma_{a_1}^2 + a_2^2 \sigma_{a_2}^2}{(a_1^2 + a_2^2)} \tag{14}$$

Finally, the error estimate of the regional slope calculations in degrees is obtained by

$$\sigma_\nabla{}^\circ = \tan^{-1}(\sigma_\nabla^2)^{1/2} \tag{15}$$

The surface distance subtended by one degree of latitude decreases as the cosine of latitude. Thus, for the 1° Venus and earth data, the regional slopes are calculated over smaller

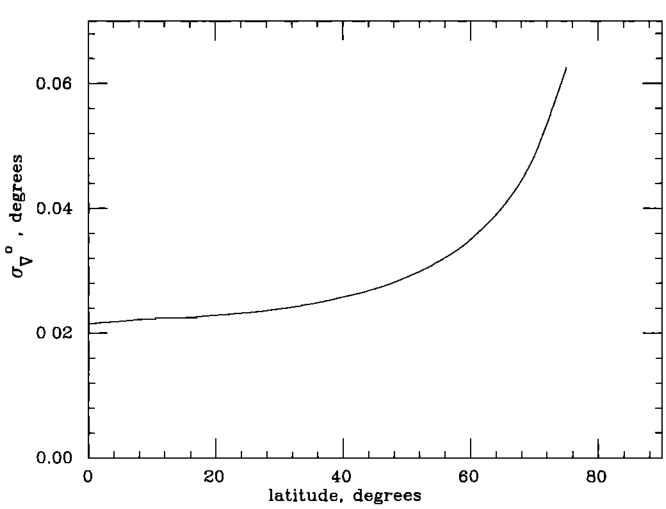

Fig. 7. Latitude dependence of the standard error in regional slope calculation derived by assuming a 100-m error in elevation measurements and equal weighting of latitude and longitude partial regression coefficients.

areas at higher latitudes. If a constant vertical error of 100 m is assumed, $\sigma_V°$ increases with latitude, as shown in Figure 7. Over 90% of the data occur within 60° and therefore have errors less than 0.035°; all data have standard errors less than 0.07°. Therefore we conclude that a reasonable estimate of the standard error associated with the regional slope data is 0.035° and the 0.95 confidence interval about each regional slope measurement is 0.07°.

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