Principal Component Analysis of Terrestrial and Venusian Topography

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Abstract

We use Principal Component Analysis (PCA) as an objective tool in analyzing, comparing, and contrasting topographic profiles of different/similar features from different locations and planets.

To do so, we take average profiles of a set of features and form a cross-correlation matrix, which is then diagonalized to determine its principal components. These components, not merely numbers, represent actual profile shapes that give a quantitative basis for comparing different sets of features. For example, PCA for terrestrial hotspots shows the main component as a generic dome shape. Secondary components show a more sinusoidal shape, related to the lithospheric loading response, and thus give information about the nature of the lithosphere setting of the various hotspots.

We examine a range of terrestrial spreading centers: fast, slow, ultra-slow, incipient, and extinct, and compare these to several chasmata on Venus (including Devana, Ganis, Juno, Parga, and Kuanja). For upwelling regions, we consider the oceanic Hawaii, Reunion, and Iceland hotspots and Yellowstone, a prototypical continental hotspot. Venus has approximately one dozen broad topographic and geoid highs called regiones. Our analysis includes Atla, Beta, and W. Eistla regions. Atla and Beta are widely thought to be the most likely to be currently or recently active.

Analysis of terrestrial rifts suggests shows increasing uniformity of shape among rifts with increasing spreading rates. Venus' correlations of uniformity rank considerably lower than the terrestrial ones. Extrapolating the correlation/spreading rate suggests that Venus' chasmata, if analogous to terrestrial spreading centers, most resemble the ultra-slow spreading level (less than 12mm/yr) of the Arctic Gakkel ridge. PCA will provide an objective measurement of this correlation.

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Introduction

Earth and Venus have many similar features, yet their tectonic histories are quite different. Like the Earth, Venus has a global rift system, which has been cited as evidence of tectonic activity, despite the apparent lack of Earth-style plate tectonics. Both systems are marked by large ridges, usually with central grabens. On Earth, the topography of the rifts can be modeled well by a cooling half-space and the spreading of two divergent plates. The origin of the topographic signature on Venus, however, remains enigmatic. Venus' rift zones (termed "chasmata") can be fit by four great circle arcs extending 1000s of kilometers. This chasma system measures 54,464 km [Parsons, 1981], which, when corrected for the smaller size of Venus, nearly matches the 59,200-km total length of the spreading ridges determined for Earth [Jurdy and Stefanick, 1999]. Venus and Earth also both have large regions of apparent upwelling - hotspots on Earth, and regiones on Venus [Stofan and Smrekar, 2005]. These are marked by broad topographic and geoid highs as well as evidence of volcanic activity.

We use topographic profiles to look for well-understood terrestrial analogs to venusian features. Specifically, we cross-correlate average profiles for terrestrial rifts (slow and fast, incipient and inactive) and hotspots (oceanic and continental) with those for venusian chasmata and regiones, and draw inferences as to the processes responsible for shaping Venus' surface.

Features

800-km profile lines used for rifts (Earth) and chasmata (Venus), and 800-km and 1200-km profile lines used for presumed mantle upwellings on both. Polar projection (Arctic map) and Eckert-IV projection for Earth and Venus maps.

Procedure

Using Magellan topography data for Venus, and ETOP05 for Earth, and techniques described more fully in Stoddard and Jurdy [2009], we compare profiles of venusian chasmata (Devana, Ganis, Parga, Juna, "Lambda") terrestrial spreading rifts: mid-ocean ridges, both fast (Pac/Naz, Coc/Pac, Pac/Ant) and slow (NAm/Eur, Afr/NAm, Afr/SAm); the ultra-slow, intermittent Arctic ridge; continental E. African Rift; and the extinct Labrador rift.

First, we analyze this set of terrestrial spreading features with known spreading rates. Next, we compare a subset of Earth ridges (fast, intermediate, slow, ultra-slow and continental) with an equal number of Venus' chasmata: Ganis Chasma on Atla Regio and Devana Chasma, which extends from Beta Regio to Phoebe Regio [Price and Suppe, 1995], and Juno, Parga, and Lambda. On Venus, these rifts rank among the most recently active features [Basilevsky and Head, 2002] with profuse volcanism as documented by the nature of cratering.

We cross-correlate the average profiles of each feature with each other to arrive at our correlation matrix, diagonalizing the matrix for the eigenvalues, or principal components (PCs). Each feature's profile can be sythesized by a weighted sum of the PC profiles.

Steps:
- average profiles
- correlate with each other
- form correlation matrix
- diagonalize for PC analysis
- synthesize each feature

Ternary Diagrams for Principal-Component Analysis
We use ternary diagrams modified to allow plotting of variables with negative values to display relative strengths of the top three principal components (PC). The center triangle is the standard ternary, with all three variables (principal components) positive. Each of the adjacent three triangles has one negative variable. Each of the outermost three triangles has two negative variables. There were no features having three negative variables.

Terrestrial Rifts

Feature	PC 1	PC 2	PC 3
Afr/NAm	0.512	0.073	-0.415
Afr/Sam	0.524	0.074	-0.401
Arctic	-0.166	0.804	-0.030
Coc/Pac	0.509	-0.026	-0.465
E. Afr Rift	0.327	-0.017	0.656
Labrador	-0.369	-0.136	-0.496
NAm/Eur	0.595	0.164	-0.240
Pac/Ant	0.610	0.151	-0.239
Pac/Naz	0.478	0.077	-0.445

Venus/Earth Rift Comparison

Feature	PC 1	PC 2	PC 3
Afr/NAm	0.663	0.229	0.108
Arctic	-0.270	0.679	-0.050
Devana	0.304	0.194	-0.502
E. Afr Rift	0.454	0.060	-0.486
Ganis	0.284	0.038	0.678
Juno	-0.085	0.623	0.292
"Lambda"	0.470	0.111	-0.419
Pac/Ant	0.678	0.295	0.028
Pac/Naz	0.715	0.269	0.015
Parga	0.423	0.189	0.388

Top 3 PC values, normalized so that absolute values sum to 1 (used as co-ordinates for ternary diagrams at left). Color coded to previous diagrams.

Top: Principal component profiles, in order of relative importance (largest eigenvalues at top). Bottom: Topographic profiles (black lines) of features analyzed in this study compared with profiles synthesized from PC profiles (blue lines). Left: Terrestrial rifts. Right: Venusian and terrestrial data set.

Average Profiles

Average profiles for the 15 rifts on Earth (blue) and Venus (orange).

Covariance Matrix for Terrestrial Rifts

Ternary diagrams for terrestrial rifts (left) and selected terrestrial rifts with an equal number of venusian chasmata (right).

Results

TERRESTRIAL SPREADING CENTERS
- PC decomposition fits very well:
  a. The top 3 PCs contain 98% of the topographic shape information
  b. The top 4 PCs contain 100%
- PC1 shows simple uplift shape
  a. PC1 is positive for all continuously active spreading ridges, including the E. Afr. Rift
  b. PC1 is negative only for Labrador (extinct) and the Arctic (intermittent, ultra slow)
- PC2 reflects Arctic rift topography
- PC3 is dominated by a central trough
  a. PC3 is negative for all active mid-ocean ridges
  b. PC3 is positive for the E. African Rift
- Ternary diagram ("PC-space"):
  a. actively spreading ridges cluster
  b. E. Afr. Rift (continental), Labrador (extinct), and Arctic (ultra slow) are isolated in PC space

EARTH SPREADING CENTERS AND VENUS CHASMATA
- PC decomposition fits at a lower level; i.e., 88% for PCs 1-3; 95% for PCs 1-5
- PCs are less-well defined than for terrestrial-only case
- Earth's active spreading centers cluster
- Venus chasmata scatter; Devana and "Lambda" plot near E. African Rift
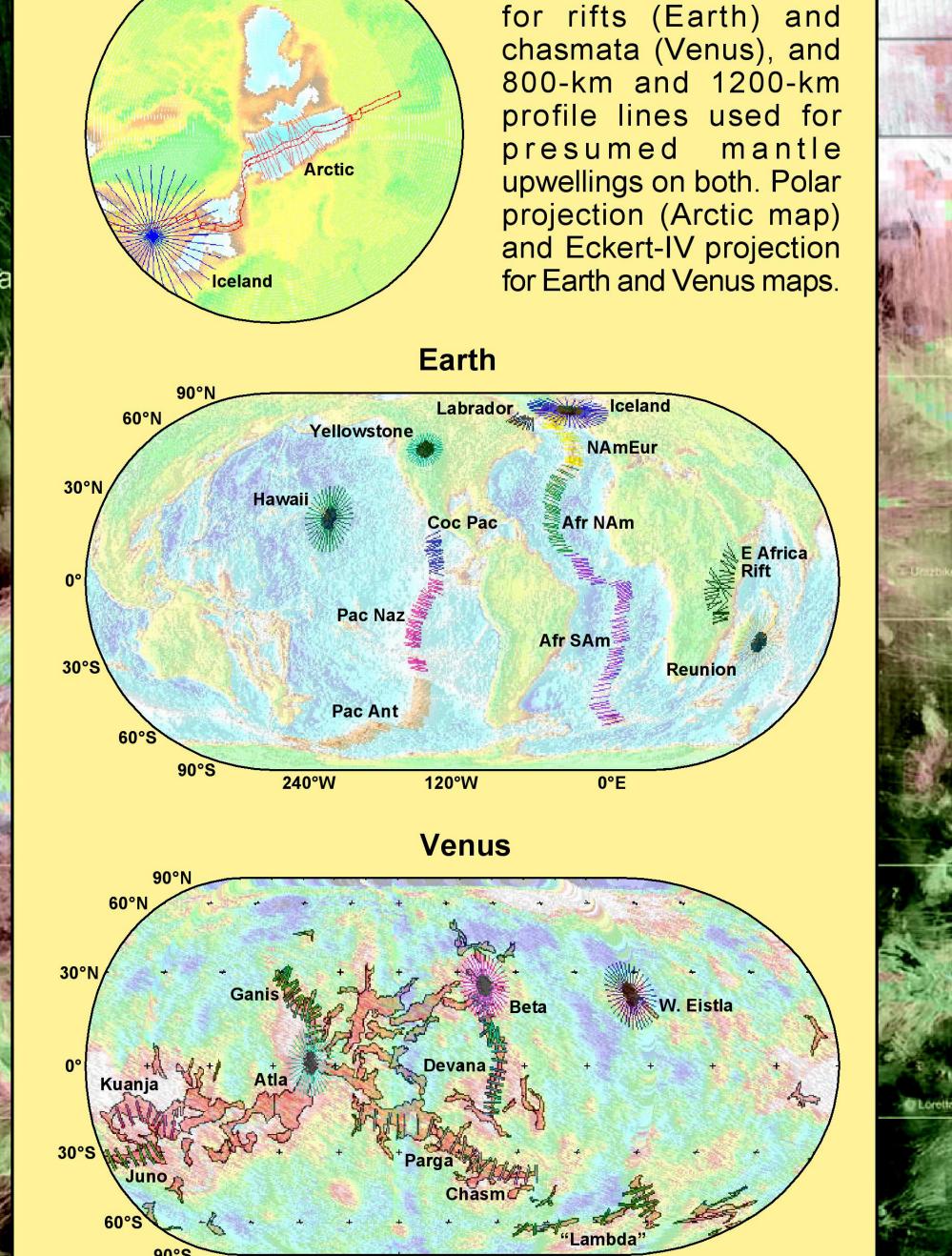- PC1 is generally positive for Venus' features and Earth's active ridges
- PC3 to be negative for chasmata

Conclusions

- Active mid-ocean ridges on Earth have similar and consistent topographic profile shapes; allows for a better fit of each profile using fewer PCs
- Venus chasmata and Earth's non-typical ridges display much more variability in topographic profile
- Since chasmata plot more like the Arctic and E. African rifts, we suggest that chasmata are ultra-slow spreading rifts in a thick lithosphere. A previous topographic study (REF) found that Atla and Beta regiones most closely resembles Yellowstone, another indication of a thick lithosphere for Venus