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Depth profiles of venusian sinuous rilles and valley networks

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ABSTRACT

More than 200 venusian channels and valleys have been mapped based on analyses of Magellan SAR images. Sinuous rilles are the most abundant channels among six types of venusian channels, and they are widely distributed on Venus. Morphological characteristics of venusian sinuous rilles include sinuous narrowing reaches, source depressions, and length of several 10s to a few 100s of km. This type of channels is known to exist on the Moon and possibly on Mars. Valley networks on Venus often occur in the vicinity of or in connection to sinuous rilles. Cross-sectional morphologies of sinuous rilles and valley networks are of special importance in discussing their formation processes both qualitatively and quantitatively. We reconstructed cross-sectional profiles of 6 sinuous rilles and 2 valley networks using a new radar clinometric method. Reconstructed cross-sections revealed that floors of the channels and valleys are clearly lower than the surrounding plains. This finding implies that the sinuous rilles and the valley networks have erosional origins. Longitudinal depth profiles of the sinuous rilles show distinct decreasing trends toward the termini. Such decreasing trends of depths are qualitatively in agreement with theoretical models and laboratory experiments of thermal erosion. In order to verify this assertion quantitatively, we conduct simple 1-dimensional model calculations under the assumption that both channel-forming lavas and ground substrate are tholeiitic basalt. For initial lava thicknesses in the range 2–6 m, the model calculations yield good matches to the depth profiles. Estimated duration of lava effusion ranges from several months to a few years. These numerical results support thermal erosion of the sinuous rilles but do not necessarily exclude contributions from mechanical erosion processes. Valley networks seem to have formed under a strong structural control in comparison to sinuous rilles. The valleys vary widely in characteristics of the depth profile and flow directions relative to surface slopes. Therefore valley networks appear to have originated from diverse formation mechanisms.

1. Introduction

Channels are widely distributed on Venus and have a great diversity of both scale and morphology (Komatsu et al., 1993). It is generally considered that these channels are associated with a wide variety of volcanic activity on Venus (Komatsu et al., 1992; Gregg and Greeley, 1993; Kargel et al., 1994; Bussey et al., 1995; Baker et al., 1997; Williams-Jones et al., 1998; Lang and Hansen, 2006; Bray et al., 2007; Oshigami and Namiki, 2007). In contrast, some previous works suggest channel formation in an aqueous environment (e.g., Jones and Pickering, 2003) or by particulate gravity currents (Waltham et al., 2008). The origin of venusian channels has been an unresolved issue since their discovery on Magellan images.

In general, formation of lava channels includes erosion and construction. Erosion is further divided into thermal and mechanical. These two processes of erosion could be distinguished by variations in depth along a channel. The depth of a thermally eroded channel decreases with increasing distance from the source (e.g., Williams et al., 2001), while the depth of a mechanically eroded channel is highly variable along the channel (e.g., Selby, 1985). Construction is the process whereby an embankment of lava flows forms on the ground by solidifying part of the fluid. Therefore constructional channels are characterized by levees or flow margins.

In this paper, we investigate characteristics of cross-sectional morphology of a particular type of venusian channels called sinuous rilles that have been proposed to be lava channels, and of valley networks that are sometimes associated with sinuous rilles (Komatsu et al., 1993), aiming to constrain the formation processes. Cross-sectional morphology of channels is crucial for qualitative and quantitative discussion of their formation processes (e.g., erosion vs. construction, thermal vs. mechanical). Channel depth of some sinuous rilles near their source region was estimated on the basis of radar foreshortening observed in Synthetic Aperture Radar (SAR) images and stereo SAR images. The estimated values are up

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Table 1
Summary of 6 sinuous rilles investigated in this study.

Label	Location	Ratio of width to depth	Correlation coefficient between depth and distance	Correlation coefficient between depth and width	Sinuosity
(a)	56.6° S, 1.2° E	47	−0.9	1.0	1.1
(b)	52.4° N, 259.4° E	77	−1.0	0.7	1.1
(c)	33.2° S, 16.6° E	21	−0.8	0.9	1.1
(d)	27.3° N, 304.7° E	46	−0.7	0.5	1.2
(e)	58.4° S, 350.1° E	48	−0.9	1.0	1.1
(f)	67.4° S, 358.2° E	48	−0.8	0.9	1.0

to a few 100s of meters (Komatsu et al., 1993). However, this estimate is subject to a few 100s of meters of cross-track resolution for Magellan SAR images (Ford et al., 1993). Recently, Oshigami and Namiki (2007) developed a new method to reconstruct fine-scale topography using Magellan SAR image brightness. They revealed cross-sectional morphology of Baltis Vallis, the longest canali-type channel on Venus with a total length of 6800 km (Baker et al., 1992) or longer (Bray et al., 2007). Sinuous rille is the most abundant type among the observed venusian channel (Komatsu et al., 1993). They have also been found on the Moon (e.g., Hulme, 1973) and possibly on Mars (Leverington, 2006). Thus the interpretation of detailed morphology and origin of venusian sinuous rilles possibly contributes to the understanding of magmatism not only on Venus but also on other planetary bodies.

In subsequent chapters, we briefly introduce adopted data sets and the radar clinometric method (Oshigami and Namiki, 2007), then reconstruct cross-sections of 6 sinuous rilles (Table 1, Fig. 1) and 2 valley networks (Table 2, Fig. 2). As we discuss later, assumptions taken in the radar clinometric method restrict the number of channels and valleys of which cross-sections are to be reconstructed.

At the end, we discuss their formation mechanisms and fluids that may have been involved. We also show depth profiles derived from numerical calculations of a thermal erosion model for the purpose of evaluating our morphologic interpretation quantitatively.

2. Radar images and altimetry data

We use Magellan Full-Resolution SAR Map (FMAP) as a source of brightness data. FMAP images are produced by the US Geological Survey. The FMAP covers about 92% of the planetary surface (Ford et al., 1993). The image pixel size of FMAP is 75 m in both cross-track and along-track directions. Full-resolution images were obtained during three mapping cycles with different look angles. It should be noted that the spatial resolution of the original images in both cross-track and along-track directions is lower than the pixel size in FMAP. The cross-track resolution is about 100 to 250 m and the along-track resolution is 110 m for cycle 1 images, for example (Ford et al., 1993).

Altimetry Data File (ADF) in the Magellan Altimetry and Radiometry Composite Data Records (ARCDR) are also used to reconstruct longitudinal profiles along channels and valleys or to evaluate the average slope of the surrounding plains. The ARCDR is produced by the Center for Space Research, Massachusetts Institute of Technology. ADF contains one data record for each altimeter footprint. The footprint size varies from 8 to 15 km along track and from 12 to 27 km across track (Ford et al., 1993). We carefully choose altimetry data on smooth terrain so that each altimetry data point represents the average altitude within a large surface footprint.

3. Reconstruction of cross-sectional profiles from SAR images

3.1. Overview of the approach

We reconstruct cross-sectional profiles using a new radar clinometric method developed by Oshigami and Namiki (2007). In this method, Muhleman's backscattering function (Muhleman, 1964) is applied to brightness data derived from SAR images. We take cycle 1 (left-looking) or cycle 2 (right-looking) images here. An important component of this method is stacking of brightness along the flow to eliminate both random noise in the radar images and minor undulations in the flow-ward topography. The major characteristics of the channels, such as depth and width, can be reliably determined using the global average values after removing respective slopes of regression lines of original cross-sectional profiles. The new method is described in detail by Oshigami and Namiki (2007). In the following, we describe assumptions and errors inherent in the method.

3.2. Accuracy of cross-sectional profiles

Following Oshigami and Namiki (2007), the two local parameters in Muhleman's function are assumed to be the same as global average values. We take radar foreshortening into consideration to avoid artificial distortion of cross-sectional profiles. However, it has been suggested by Kreslavsky and Vdovichenko (1997) that the reflections at the surface facing the radar could be enhanced depending on the exact shape of the surface and cause steeper slopes in reconstructed profiles. Because of this artificial asymmetry, we do not discuss details of the cross-sectional shape. Instead, we focus on the basic characteristics of the profile such as depth and width.

Taking the artificial asymmetry into account, we estimate a channel depth for each segment from the bank facing away from the radar. Fig. 3 shows the cross-sectional profiles of a sinuous rille located at 56.6° S, 1.2° E ((a) in Table 1). In Figs. 3, A, B, and C are the highest points of the flanks and the lowest point within the channel, respectively. The depth and width are defined as the height difference between A and C and the horizontal distance between A and B in Fig. 3, respectively.

Also shown in Fig. 3 are possible levees at both sides. These features could be either real surface topography, or distortion due to variations in subwavelength-scale surface roughness and dielectric constant that are neglected in the method. We consider that the latter is unlikely, since convex shape of these features indicates that variations of the surface properties appear as a set of bright and dark bands along channels and valleys. Quantitative evaluation of these possible levee structures, however, requires close examination of variable surface properties. Besides, the levee-like features is not as common as groove-like morphology. Thus, we do not argue these features any further.

Oshigami and Namiki (2007) show that the accuracy of the cross-sectional profiles improves with increasing number of stacking pixels and that the estimated error of depth of Baltis Vallis is less than 5 m for a 1-km distance in case that 20 pixels are stacked