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Channels and Valleys on Venus: Preliminary Analysis of Magellan Data

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A preliminary survey of Magellan imagery reveals more than 200 newly discovered relic channel and valley landform complexes. For purposes of discussion the channels can be classed as simple, complex, and compound. Integrated valleys also occur. Simple channels include (1) sinuous rilles that closely resemble their lunar counterparts and (2) a newly recognized long sinuous form of high width-to-depth ratio and remarkably constant width. Herein designated canali, the most spectacular of these channels is 6800 km long. One of the compound channels, an outflow complex in Lada Terra, extends over 1200 km and is up to 30 km wide. Streamlined hills and spill relationships at a cross-axial ridge are similar to features in flood channels. Venusian channels have a global distribution with most of the large canali-type channels developed on volcanic plains. Alternative hypotheses for the channel-forming processes include genesis by the following erosive fluids: ultramafic silicate melts, sulfur, and carbonate lavas. Each of these causative agents has profound implications for Venusian planetology. The remote possibility of an aqueous origin, indicated by apparent regime behavior of the active channeling process, cannot be excluded with absolute certainty.

Introduction

The discovery of abundant and diverse channels on Venus is one of the surprises of the Magellan mission. Venus is now the third known planet to have experienced widespread dissection by channelized fluids. As in the case of Mars [*Baker*, 1982], it was spacecraft remote sensing imagery that revealed the channels, whose existence was unanticipated by premission science planning.

The term "channel" implies an open conduit through which a fluid passed. In general, the fluid contacts all the boundaries of the channel, contributing to its shaping. Channels may form when preexisting depressions are modified by fluid flows. Channels can also be created when fluids cut into or deposit materials onto some surface. On Earth and Mars, water flow is responsible for the most widespread channeling, but the identities of the Venusian channel-forming fluids are enigmatic, as will be discussed in this paper.

A related term, "valley," applies to elongate depressions cut into a landscape. Valleys usually exist in interconnected groupings and have outlets for fluids that flowed on their floors. However, valleys need not have their boundaries shaped by fluid flow. Mass movement processes are responsible for most material removal from the walls of many valleys. Nevertheless, some fluid-flow process often is involved in material removal from valley floors.

This paper will discuss both channels and valleys, but emphasis will be placed on the 200 or so large channels or channel segments that were identified from Magellan imagery as of September 1991. It seems clear that many more Venusian channels and valleys will be identified through the acquisition of more imagery and by the careful scrutiny of the entire Magellan data set.

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Classification and Morphology of Channels and Valleys on Venus

A variety of channel and valley landforms can be recognized on Magellan radar images of Venus. These landforms exhibit a diverse range of morphological features commonly associated with lunar sinuous rilles and lava and fluvial channels on both Earth and Mars. The channels and valleys we have documented on the Magellan radar images are classified into the four major morphologic categories: simple, complex, compound, and integrated (Figure 1). This classification is preliminary and intended merely as an aid to facilitate discussion. Examples of simple and complex channels were described respectively by *Head et al.* [1991] and by *Arvidson et al.* [1991] in the preliminary Magellan mission report.

Simple Channels

These channels are characterized by a long, single main channel and can be further divided into two subcategories: sinuous rilles and canali. Sinuous rilles closely resemble lunar channels (Figures 2, 3, and 4). They emanate from distinct source areas, usually from small (kilometers in diameter) circular collapse regions. Other source areas include large (several tens of kilometers in width and length) elongated collapse regions or even long fractures. These channels form a lunarlike

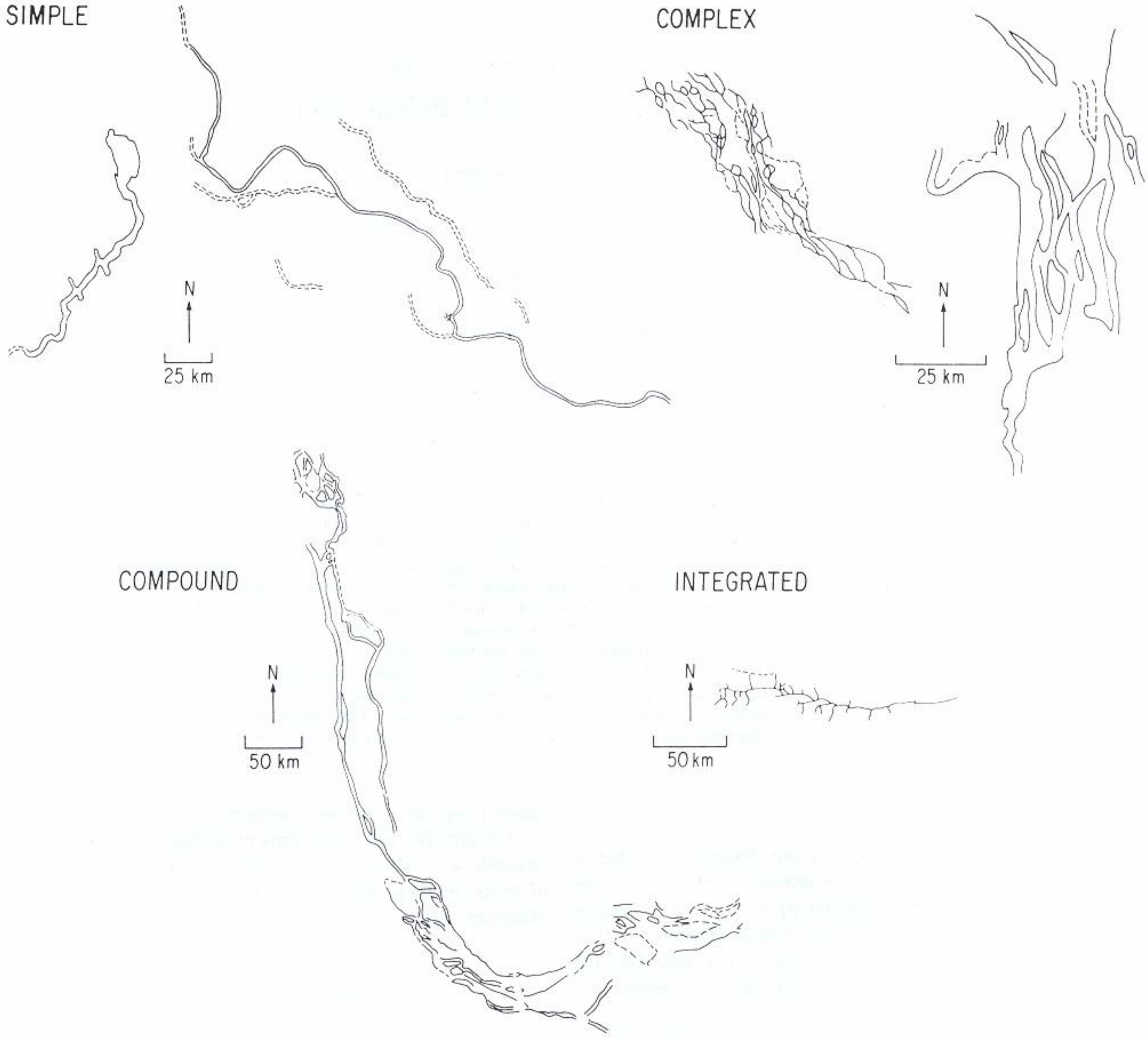

Fig. 1. Preliminary classification of channel and valley landforms on Venus [*Gulick et al.*, 1991].

deep single channel which narrows and shallows toward its terminus. Channel walls form a distinct boundary between the channel floor and the surrounding terrain into which it is carved. As with lunar sinuous rilles, flow margins are not associated with these channels. Venusian sinuous rilles, in general, have larger meander wavelengths and are more sinuous than typical lunar sinuous rilles, although width-to-depth ratios are similar. Venusian sinuous rilles are typically 1 to 2 km wide and several tens to hundreds of kilometers long. Channel material can either be radar bright or dark and is similar to the surrounding terrain material. The sinuous rilles are usually associated with coronae or can be located in the plains regions. Figures 2, 3, and 4 illustrate examples of this channel type and compare them to lunar sinuous rilles.

Canali (Italian for "channels") are generally larger and longer than the sinuous rilles and may contain a few subsidiary channels which branch off from the main channel (Figure 1). In general, channels emanate from indistinct source regions and terminate in large radar-dark areas that may be depositional. Radar dark areas of possible depositional origin are also common along the smaller subsidiary branching systems. In contrast to the sinuous rilles, the widths of canali remain relatively constant downchannel and range from approximately 3 to 5 km. Lengths can exceed several hundreds of kilometers. Channel width to depth ratios are generally much larger than those for the sinuous rilles. Cutbank relationships, a cutoff meander bend, and relic, abandoned paleochannels are apparent in the one of the larger examples of this channel type located in Guenevere Planitia and centered at 3°N, 335° (Figure 5). Figure 6 shows another example. Canali can be either radar bright or dark and are generally located in broad valley or plains regions. Walls of channels, particularly those containing radar dark deposits, are generally not distinct from the surrounding terrain. Channels containing radar bright deposits are commonly distinguished from surrounding terrain by a distinct pair of parallel, sinuous ridges. An unusually long canali-type channel will be described in more detail in a subsequent section of this report.

Fig. 2. Venusian sinuous rille located within a corona in the Lavinia Planitia region and centered at 58.5°S, 347°E. The channel emanates from a small circular collapse region and extends for approximately 50 km to the north until it gradually narrows and blends in with the surrounding terrain.

Fig. 3*a*. Venusian sinuous rilles located near Alpha Regio and centered at 24.3°S, 347°E.

Complex Channels

Complex channels (Figure 1) include anastomosing or braided patterns. Branching patterns, usually distributary, can also be included in this category. Channels are commonly separated by "islands" of radar-bright (or dark in some cases) material. Margins are sometimes lined with radar-bright material. Individual channel widths range from approximately 3 km down to the limit of resolution, while the total width of the channel system can range from 20 to 30 km and lengths up to a hundred kilometers. Channels emanating from the fluidized ejecta blankets (FEBs) of impact craters tend to form anastomosing or braided patterns. Figure 7*a* shows complex channels on the fluidized ejecta blanket of the crater Aglaonice. These channels are approximately 50 km long.

Channels located on flow deposits are also included in this category. The channels on the enormous flow deposits of Mylitta Fluctus (Figure 7*b*) located in southern Lavinia Planitia display braided or anastomosing patterns. Toward the ends of other flow features, channels form a complex, distributary

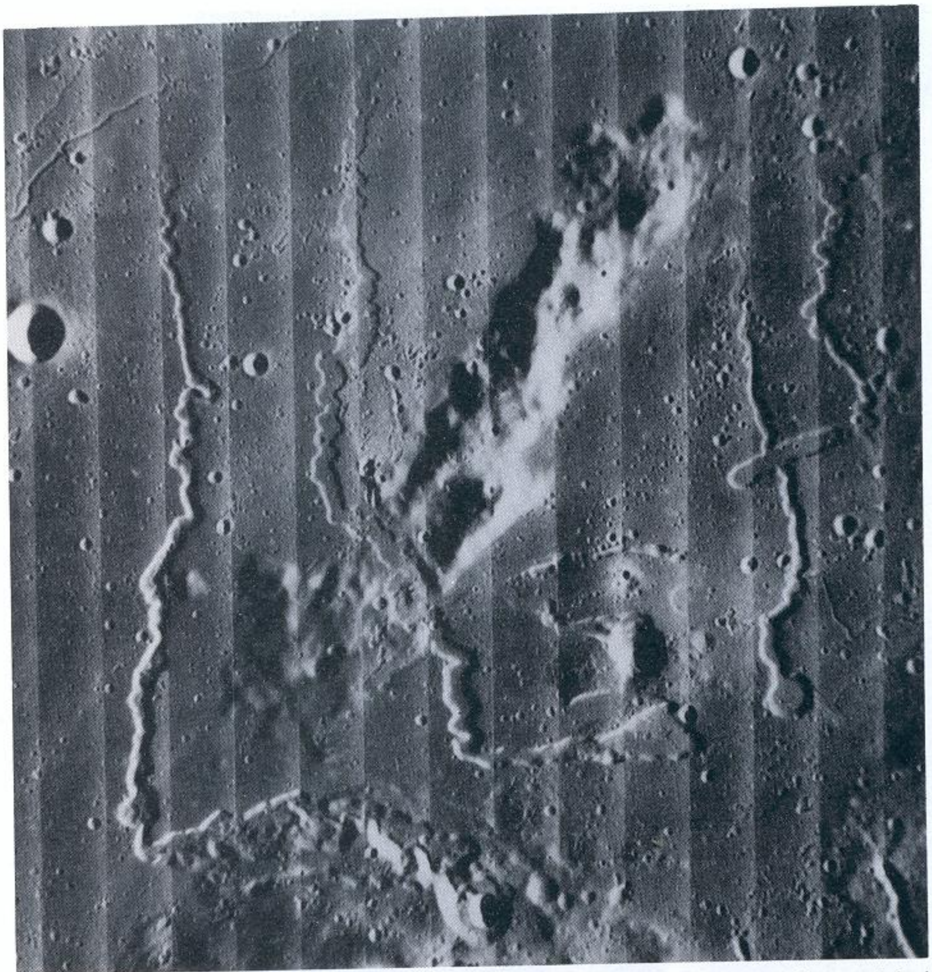

Fig. 3*b*. Lunar sinuous rilles located at 27°N, 43°W (lunar orbiter mosaic LO V-M-190). Note the morphologic similarity between rightmost lunar sinuous rille and the Venusian channel (see Figure 3*a*).

patterns. Southeast of Aphrodite Terra (Figures 7*c* and 7*d*) radar-dark channels branch off from the main channel and extend over a radar-bright deltalike flow feature. Individual channels gradually decrease in width toward the end of the delta-like feature where they appear to terminate. This morphology is consistent with the genetic association of the channels with features, such as Mylitta Fluctus, ascribed by *Head et al.* [1991] to volcanic origin.

Compound Channels

Compound channels (Figure 1) are characterized by both simple and complex segments. Simple segments tend to form in mountain regions or areas that are structurally controlled, and they return to a braided or distributary pattern in plains or broad valley regions. Extensive flow deposits are often located where a channel debouches onto open plains regions or at the channel terminus. The largest channel in this class, informally named the "outflow channel" (47.5°S, 19°E) contains stream-lined hills and an anastomosing pattern analogous to those observed in Martian outflow channels [*Baker*, 1982]. The "outflow channel" is described in more detail in a subsequent section. Another compound channel is illustrated in Figure 8.

Fig. 4*a*. Venusian channels located just north of Ovda Regio. The radar image is centered at 11.4°S, 89.5°E and is approximately 110 km wide. Note the enlarged fractures and elongated collapse regions for source areas and the sharply defined channel walls.

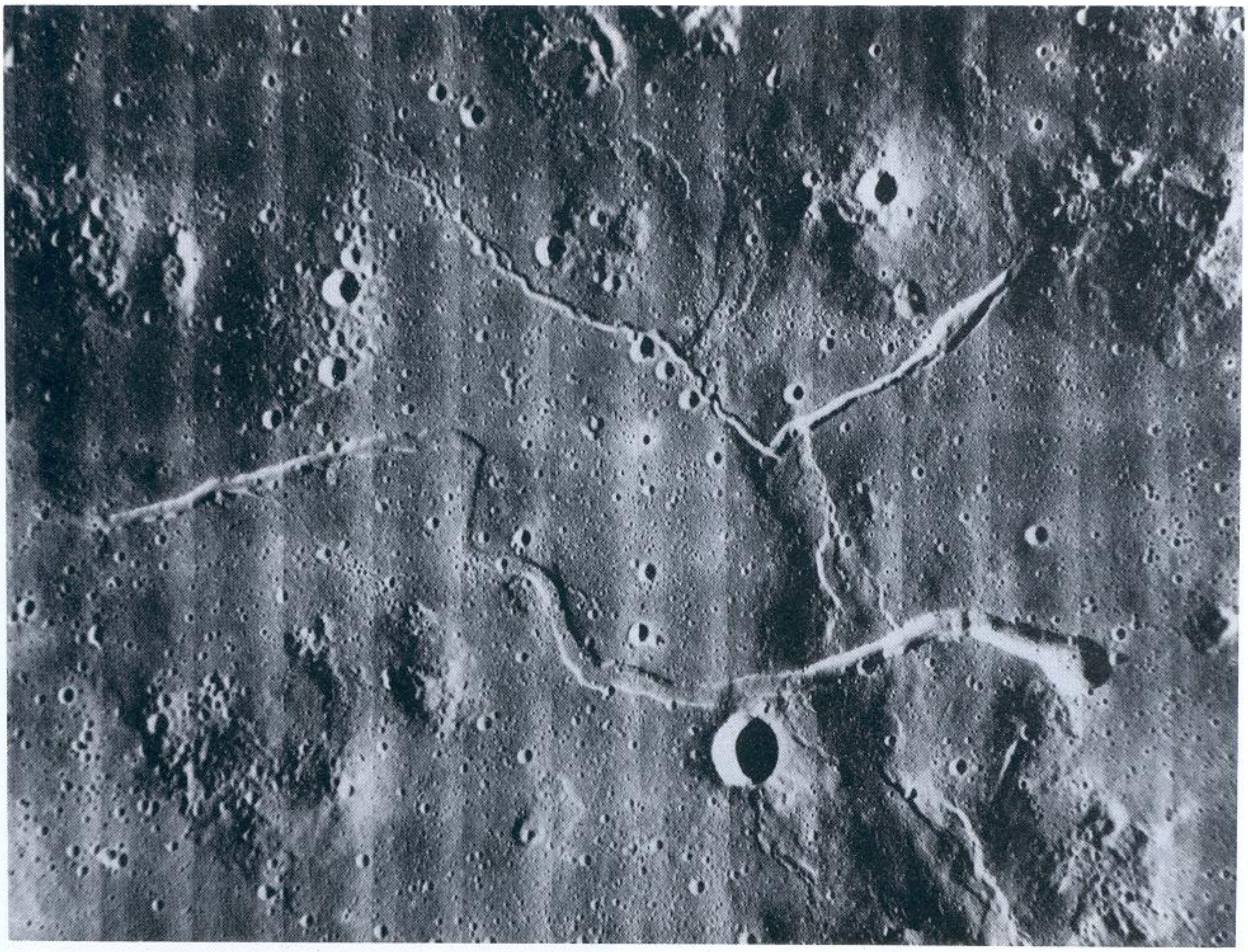

Fig. 4*b*. Lunar sinuous rilles emanating from elongated collapse troughs. Lunar orbiter mosaic centered at 57°W, 14°N (LO V-M-213).

Fig. 5*a*. Simple canali-type Venusian channel located in southwest Guenevere Planitia (3°N, 335°E). Channel is over 600 km long.

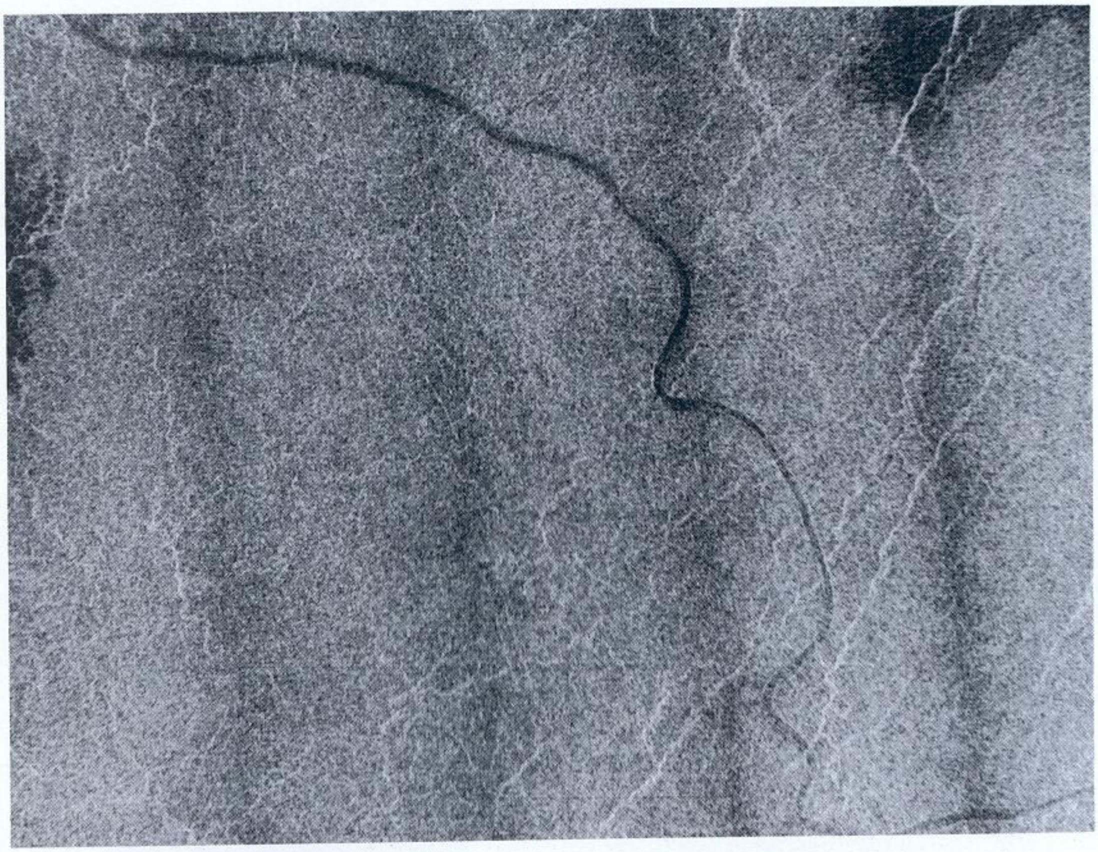

Fig. 5*b*. Cutoff meander loop in the southwest Guenevere Planitia channel.

Compound channels vary greatly in size, with widths of between several tens of kilometers in complex regions down to the limit of resolution in the simple reaches. Total lengths can range from 75 km to thousands of kilometers.

Integrated Networks

Integrated networks (Figure 1) form a complex system of branching valleys with similar morphologies to those produced by sapping processes on Earth and Mars [*Baker*, 1990]. These landforms are distinct from the other Venusian channels in that they appear to have formed by the undermining and subsequent collapse of surface material by outflow of a low-viscosity subsurface fluid. The most integrated valley system, located at 2°N, 70°E, is over 50 km long, is less than a kilometer wide, and contains at least 15 first-order and 5 second-order tributaries (Figure 9*a*). It is located in a narrow (15 km wide) radar-dark plains region. The lack of surrounding surface fractures argues against this feature being purely tectonic in origin. Similar morphology is common on both Earth and Mars where previously buried fracture patterns are eventually reexposed by the outflow of ground water in the formation of a sapping valley network. A similar example of an integrated network, though not quite as developed, is centered at approximately 8.8°S, 84°E (Figure 9*b*). In contrast to the previous example, this network appears superimposed on a fine textured system of fractures which trend northwest-southeast and curve around to trend northeast-southwest direction. The network trends northwest-southeast and cuts nearly straight across the curving fracture system at an angle. Both systems display a complex network of stubby, theater-headed subsidiary valleys. However, because of uplift to the east of both networks, it is not known whether these branching valleys are actually tributaries or distributaries.

Another unique and somewhat bizarre valley system has been discovered at 3°N, 304°E in an area of relatively smooth plains. The plains contain linear ridges (Figure 9*c*) and exhibit both radar-bright and -dark regions resulting in a mottled surface appearance. The valley system is over 300 km long, with the main trunk valley widening from a minimum of several kilometers to a maximum of approximately 50 km. It appears to have formed by a system of coalesced pits having diameters up to several kilometers. The widest main valley reach is surrounded by a series of larger, loosely organized pits. Narrow sections of the main valley are surrounded by smaller coalesced pits forming numerous, organized first- and second-order branching valleys, which may be tributaries. A similar, less developed valley system is located 150 km to the north. The main trunk valley is much wider, exceeding widths of 75 km, although the overall network pattern is generally less organized.

Morphometry

Simple Venusian channels exhibit morphological features characteristic of both lunar sinuous rilles and terrestrial river channels (Figure 10). Measurements indicate that meander bends of terrestrial river channels have a radius of curvature 2-3 times the channel width and a wavelength of 10-12 times the channel width [*Ritter*, 1978]. Preliminary measurements indicate that lunar sinuous rilles have considerably lower ratios,

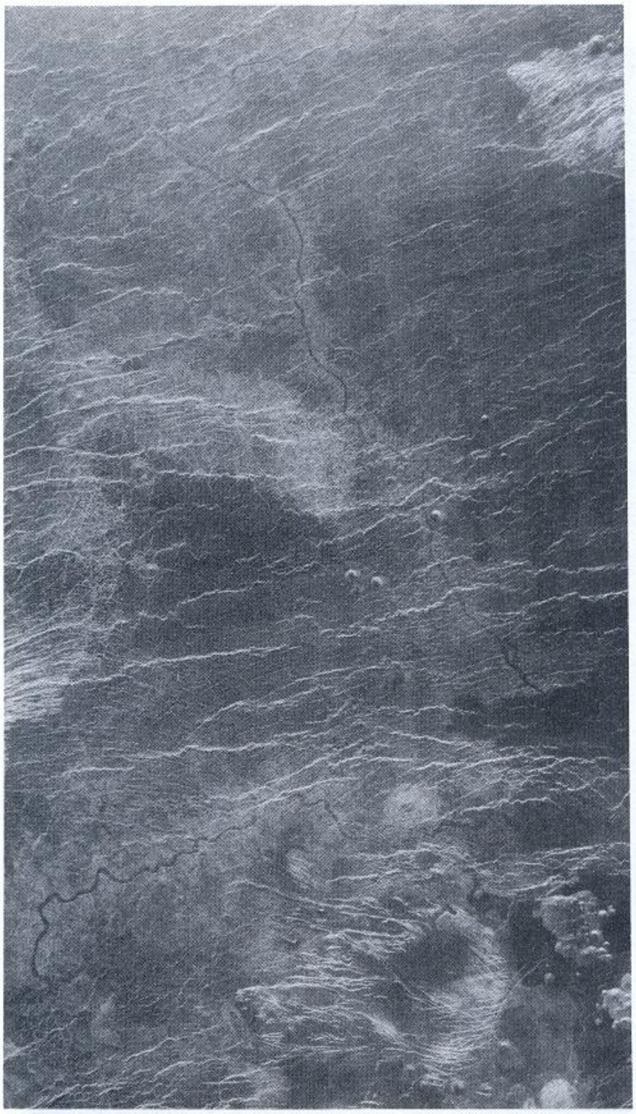

Fig. 6. Simple canali-type channel located in Helen Planitia and centered at approximately 49°S, 271°E. Image width is approximately 435 km. Canali can extend for distances of thousands of kilometers.

and Venusian channels generally have much higher ratios than those of terrestrial rivers. A preliminary conclusion is that these Venusian landforms represent a new class of channel phenomena unlike others in the solar system.

GLOBAL DISTRIBUTION AND SETTINGS

Figure 11 shows the global distribution of Venusian channels mapped as of September 1991. The mapped channels all seem to have formed by interaction between fluid material and terrain. We mapped channels which are relatively long (>100 km) and have well-defined reaches using near complete coverage of C1-MIDR (100-300 m resolution) and available F-MIDR Magellan imagery products (Figure 12). This map must be considered preliminary because of difficulties in recognizing narrow channels in mosaics and in tracing channels which are often disrupted and buried by subsequent tectonics and volcanism. However, we observe a global pattern of channel distribution. Some channels occur at most latitudes and longitudes. The highest channel altitude is about 7-8 km (66°N, 8° E, emanating from Cleopatra) and the lowest altitude is about -1 km in various plains regions. Regions of highest channel concentration include southern Guenevere Planitia, northeastern Sedna Planitia, Helen Planitia, southeast of Artemis Chasma, plains north of Rusalka Planitia, and north central Lada Terra. These are all plains regions except north central Lada Terra, which is a corona and tessera-type highland.

The mapping reveals four major geological settings of channels:

1. Most of the large canali-type channels occur on plains surface units which occupy the largest percentage of the planet. Although the plains were probably formed by many flood eruption events, it is not clear whether the flood eruptions are directly responsible for sinuous channel formation. If they were, canali may have formed as feeders for vast lava flows or by a long-sustained low-viscosity lava flow with a relatively low discharge rate.

2. Channels in this setting emanate from volcanic constructs or occur within their boundaries. They are generally small compared with channels in plains regions. This suggests that the more localized volcanism of constructs provided sufficient, but somewhat limited, conditions for channel formation. The most common volcanic constructs associated with channels are coronae. Channels occur inside corona annular deformation zones and also as feeder channels of lava flows emanating from the annular deformation zones.

3. Channels in highland regions of mainly tectonic origin are mostly concentrated in the highland plains that are the result of volcanic resurfacing.

4. Many Venusian impact craters have fluidized ejecta blankets (FEBs), which are commonly dissected by channels. Paleoflow directions generally follow topography, and, in most cases, channels are braided. The channels on FEBs are suggestive of formation by very fluid material at the time of ejecta emplacement. Hypothesized origins of FEBs include turbidity currents caused by the interaction with the atmosphere [*Schultz*, 1991], impact melts partially controlled by target surface and/or subsurface material composition and state [*Komatsu et al.*, 1991], or some combination of the two mechanisms.

CHANNEL DESCRIPTIONS

Two of the many channel complexes have been selected for more detailed description in order to illustrate the rich variety of channel landforms on Venus.

The "Outflow" Channel

A compound channel complex lies within the northern Lada Terra region, centered near 50°S, 21°E, about 15 km east of Lavinia Planitia (Figure 13). The Magellan SAR and altimetry data indicate that the channel is located on the south flank of a broad, low volcanic construct that has been named Ammavaru (the "central" vent of a large coronalike feature) at about 47°S, 19°E. The center of the construct (Figure 13*b*) appears to be a collapsed caldera lying 100-200 m elevation below the planetary mean radius of 6052 km (0 km datum) and flanked on its northeast and southwest sides by broad topographic swells with extensional graben at their crests. The northeastern swell reaches an elevation of about 800 m, and the southwestern

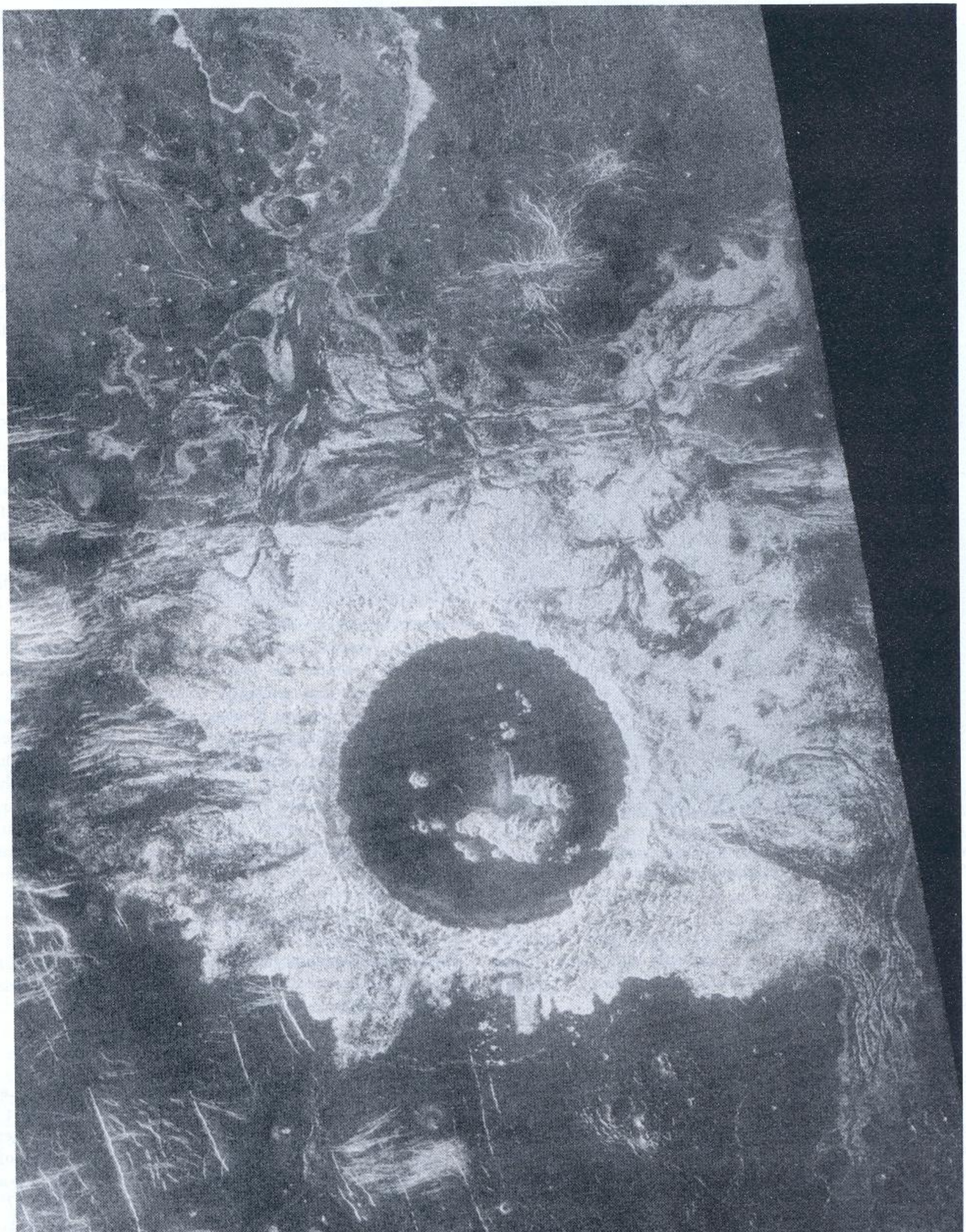

Fig. 7*a*. Example of complex channel systems. Crater Agloanice (63 km in diameter) showing complex channel pattern of fluidized ejecta blanket materials. Channels located at 27°S, 340.7°E.

Fig. 7*b*. Complex channels developed on the large-scale flow deposits of Mylitta Fluctis in southern Lavinia Planitia at 54°S, 354°E. Simple channels are also locally present. Image is 435 km across.

Fig. 7*c*. Deltalike distributary channels southeast of Aphrodite Terra at 19.5°S, 210°E. Image is 345 km across.

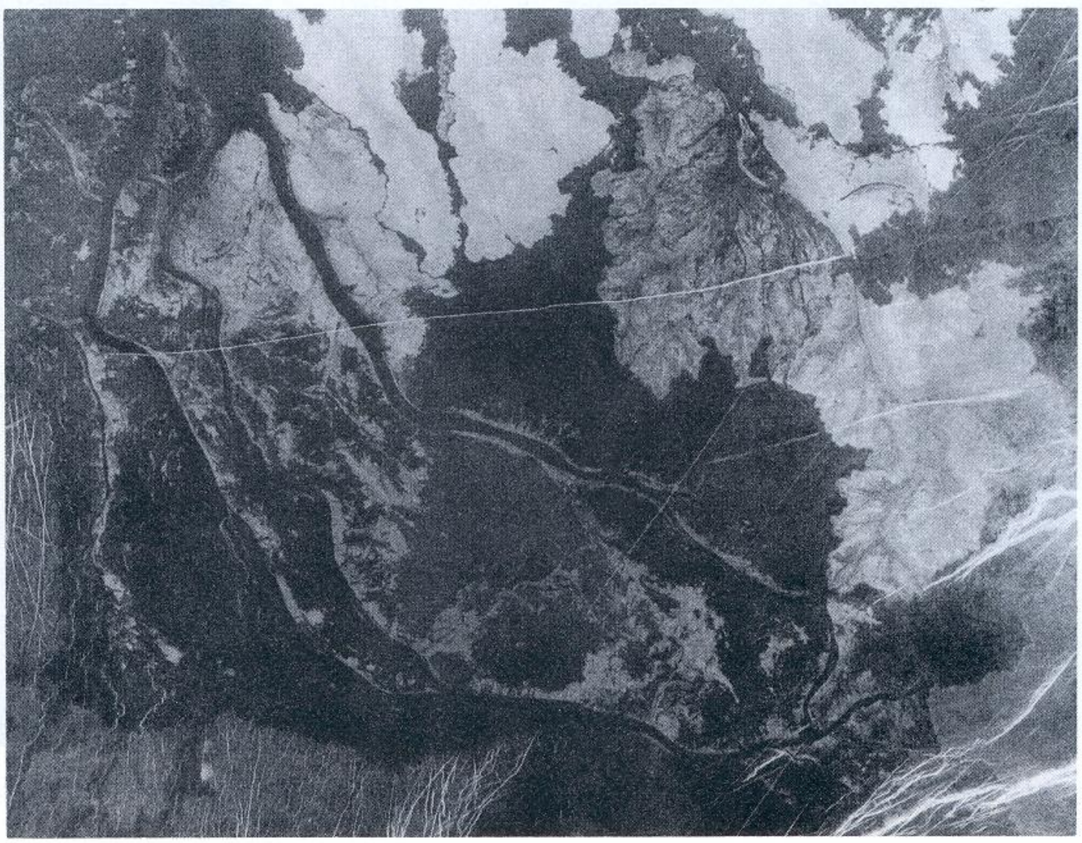

Fig. 7*d*. Deltalike distributary channels southeast of Aphrodite Terra at 20.3°S, 180.2°E. Image is 155 km across.

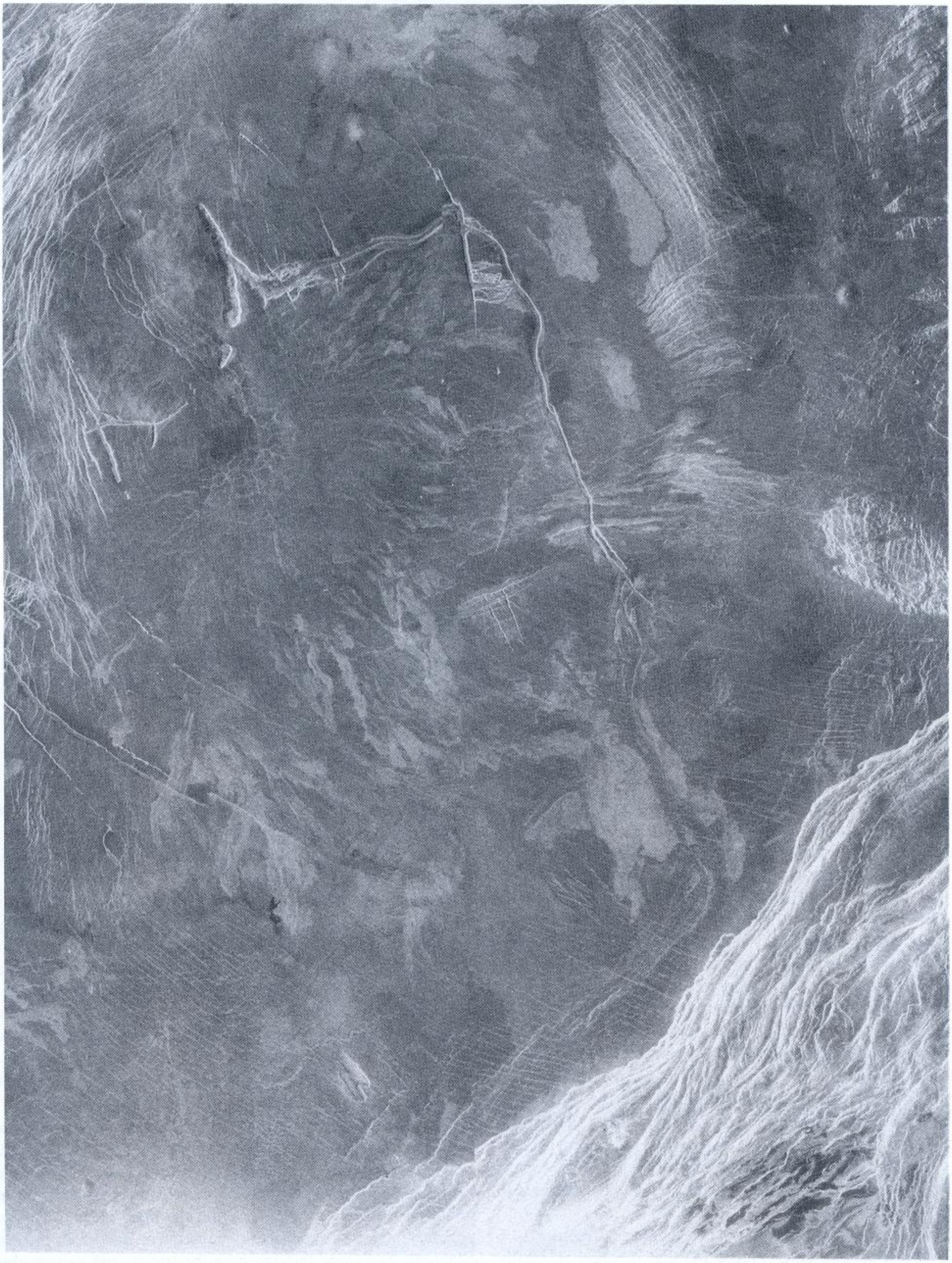

Fig. 8. Compound channel south of Ishtar Terra at 50°N, 23°E. This channel is approximately 400 km long and contains streamlined islands in its middle reach and terminates in a flow deposit.

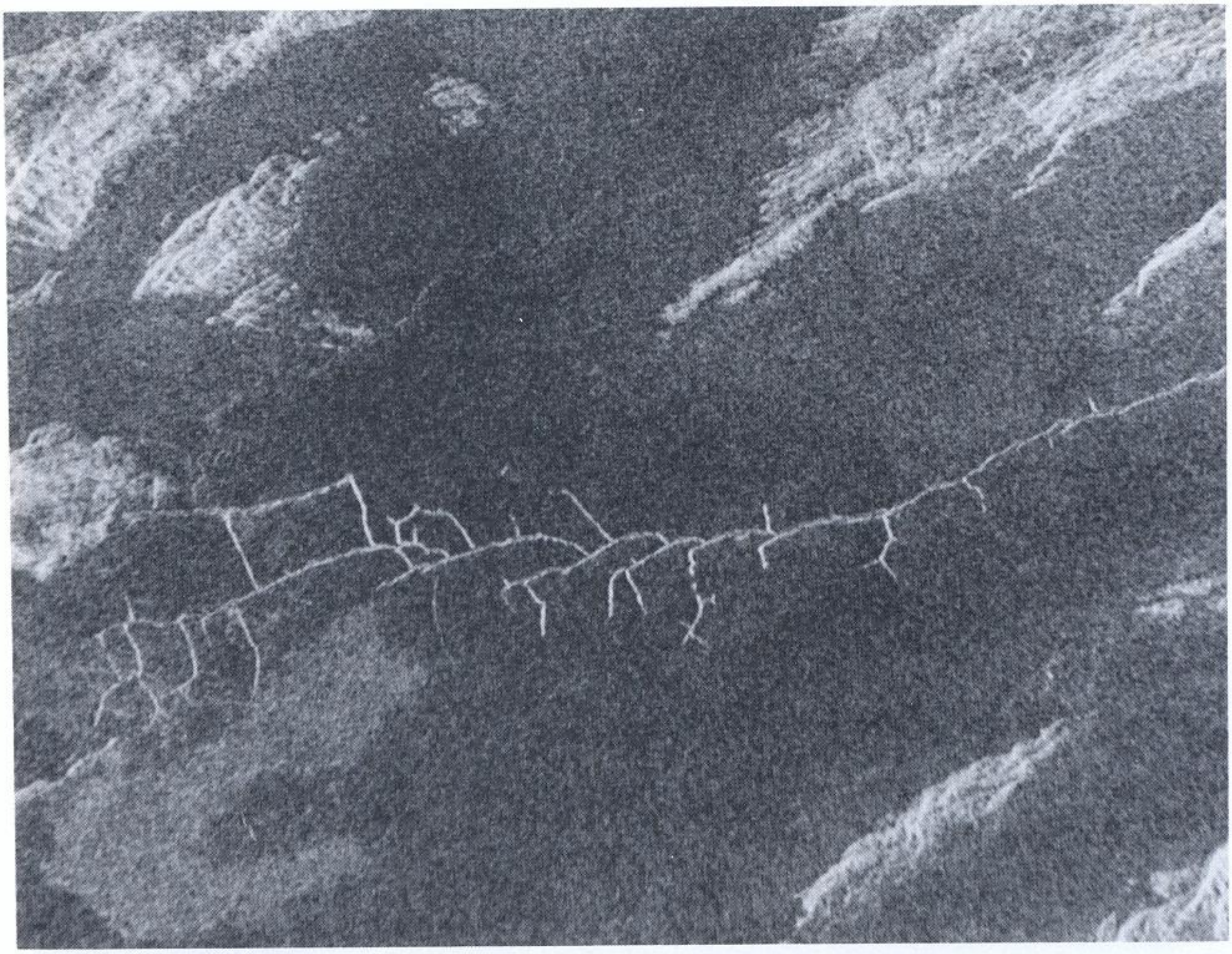

Fig. 9*a*. Integrated valley network located at 2°N, 70°E, north of Ovda Regio.

swell reaches at about 600 m elevation. Gentle slopes, typically less than 8 m/km, occur on the flanks of Ammavaru. A prominent north-northwest trending rift valley occurs southwest of Ammavaru and appears to split the coronalike feature. This rift valley is up to 50 km or more wide, is up to 800 m deep, and locally exhibits raised rims on either side. The eastern rim is elevated about 200 m above the channel, and it may have directed channel flow to the eastward, thereby preventing channel erosion into the topographically lower rift valley floor. The floor of the rift lies at an elevation of about -400 m elevation and is composed of lava derived from a channel that emanates from the northwest side of Ammavaru. To the east the outflow channel encounters a long north-south trending ridge belt at 27°E longitude, possibly defining the rim of a large corona. This ridge belt locally ranges up to about 200-300 m high. At 47°S, 27°E, this belt is breached or buried by lava flows from the west and by flows from the channel. Most of the former emanate from a field of small shieldlike structures to the east of Ammavaru.

The outflow channel originates in a collapse structure 17.5 km wide and 3.3 km long (Figure 14) that is morphologically similar to collapsed terrains at the sources of many small- to modest-scale Martian outflow channels [e.g., *Baker*, 1982; *Mars Channel Working Group*, 1983]. The collapse structure lies on the flank of the southwest peaks of Ammavaru. Magellan altimetry indicates slopes of about 2 m/km at the channel source. The channel extends from the collapse structure into a trough or graben, 300 km long and up to 5.5 km wide, trending north-northwest, subparallel to the rift. The trough appears to have been enlarged through collapse, particularly at its north end where it is linked to the collapse terrain source, and may have served as both an additional source and an initial conduit for the flow. Flow structures within the trough, if present, are at a scale below the resolution limit of the data (about 200 m at this latitude). Numerous bright specks on the plains surface east of this trough appear to be directly associated with the trough. It is not clear whether these specks indicate deposits contemporaneous with outflow or whether they are eolian features (such as dunes) that formed in the lee of the trough.

East of the trough, a narrow channel 300 km long and up to 1 km wide apparently contained a small part of the initial outflow. This channel is a shallow, radar-dark sinuous feature with radar-bright margins and occasional midstream islands. It terminates downstream before joining the main channel and was probably buried or modified by subsequent flow from the main channel. The slope through both the trough and narrow channel is about 0.5 m/km. At 51.5°S, 20.5°E, the flood spreads into a spectacular, anastomosing reach (Figure 15), flowing east to 51.5°S, 24°E. It begins near the end of the rough, apparently as a result of spillover of the trough rim. Numerous,

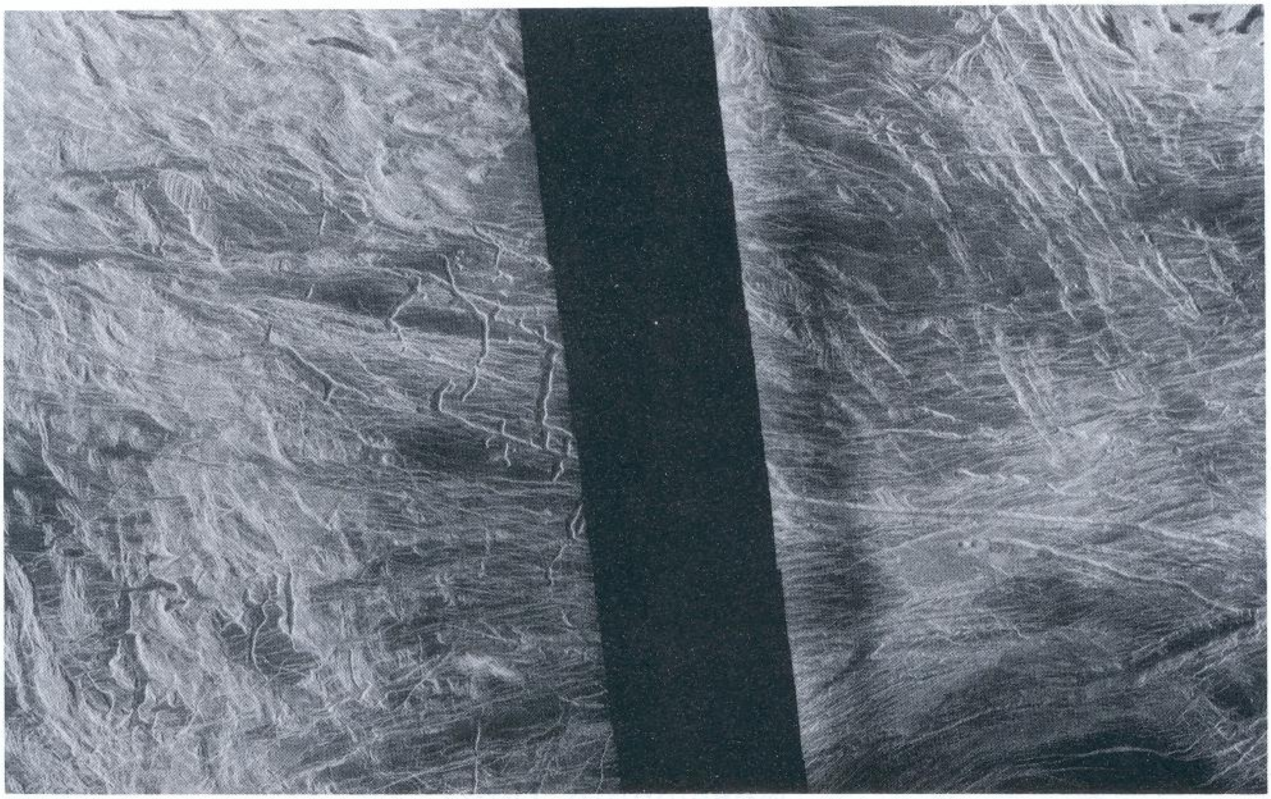

Fig. 9*b*. Network of troughlike valleys located at 8.8°S, 84°E in Ovda Regio. Radar image is approximately 400 km across.

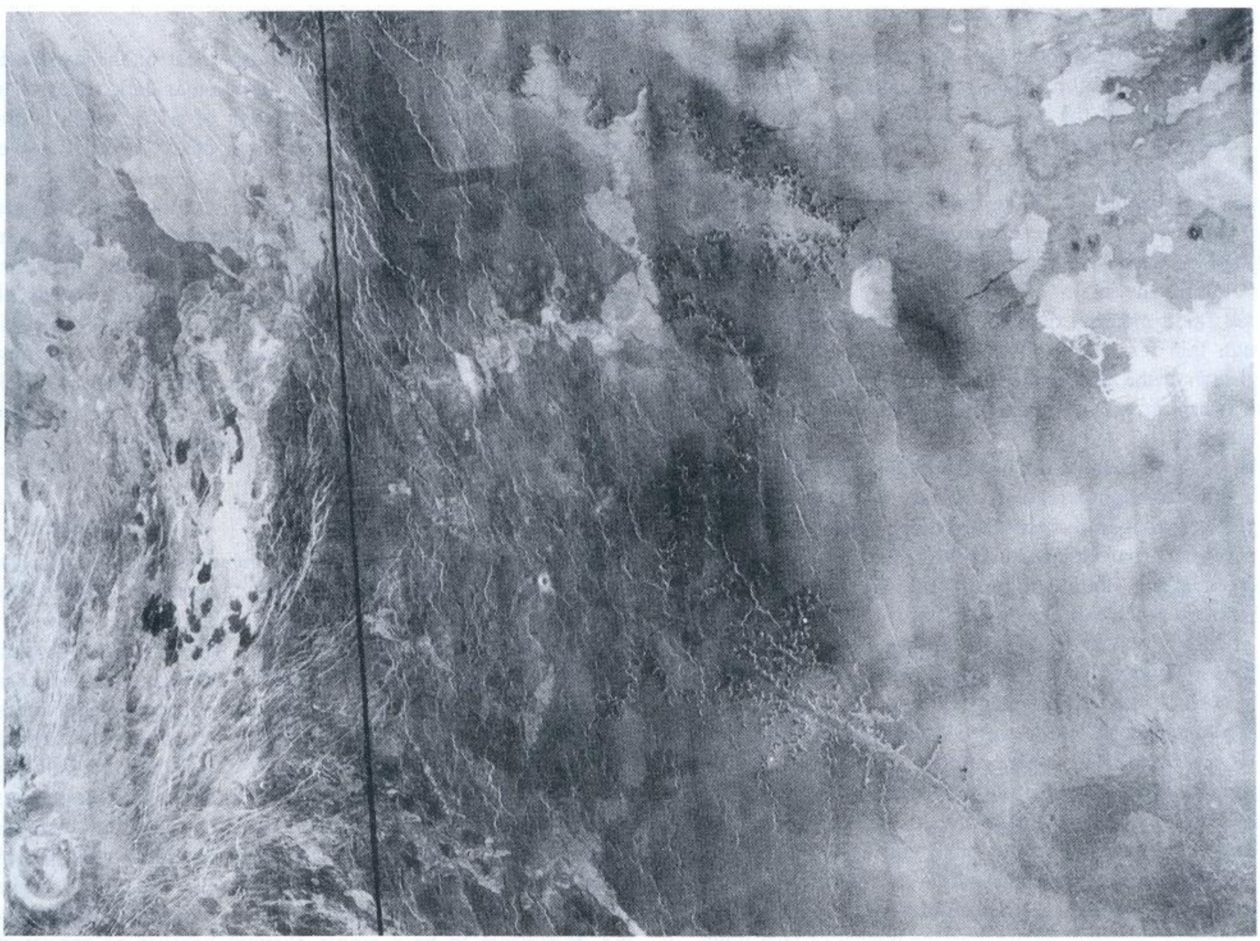

Fig. 9*c*. A distinctly different type of integrated system forming a network of irregular valleys southwest of Guenevere Planitia and located at 3°N, 304°E. Radar image is approximately 400 km across.

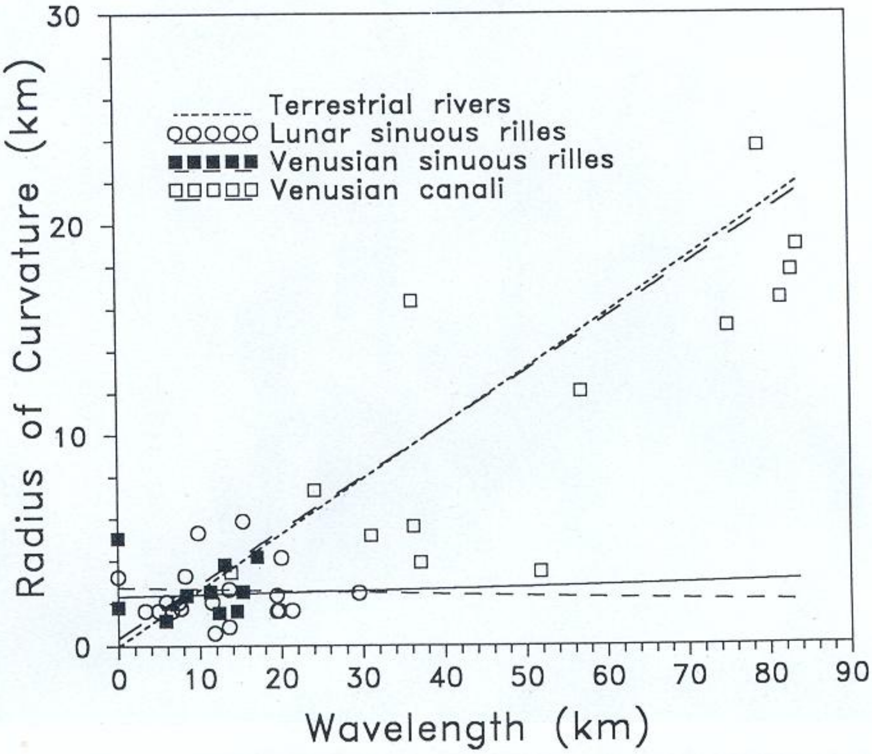

Fig. 10. Preliminary morphometric analyses of Venusian channels showing the relationship meander radius of curvature to meander wavelength. A regression line fit to the Venusian canali data is remarkably similar to the relationship shown by terrestrial rivers [*Leopold and Wolman*, 1957]. Both Venusian and lunar sinuous rills show similar meander properties.

well-developed streamlined hills (midchannel islands) suggest effective erosion of the extant plains surface. Sheet flooding prior to incision of the main channels is suggested by several faint channels to either side of the main system and by the burial of the narrow channel. At 51°S, 23.5°E, local topographic highs appear to have temporarily obstructed the outflow fluids, which then embayed the highlands until the obstructions were overtopped. The best developed streamlined hills within the main channel probably developed as the ponded flood material drained through these gaps. The slope through this reach is less than 0.5 m/km and may even be uphill toward the end, a possible indication of deflation or tectonic warping of the coronalike structure after channel incision.

East of the breach of the highlands, the flow features spread out into radar-bright irregularly lobate flow morphology. The channel branches into three distributary channels that initially are radar-dark but change to radar-bright channels with dark lateral margins about midway through the reach. This "distributary reach" continues east until it encounters the ridge belt at 51.5°S, 26.5°E. The total length of this reach is about 130 km. Individual channels range in width from 2 to 6 km.

The outflow features terminate in a partially confined, radar-bright plains deposit on the west side of the ridge from 47°S to 51.5°S, 26°E to 27°E, apparently filling a 60-km-wide trough between the ridge belt and the east flank of Ammavaru. The "main" channel branch can be traced through this deposit to just beyond the breach in the ridge belt at 47°S, 27°E, more than 300 km north of the "end" of the distributary reach.

The terminal deposit is also a radar-bright plain exhibiting well-defined irregularly lobate margins typical of lava flows. It occupies a region of about 100,000 km^2, extending from 46°S to 53°S, 27°E to about 32°E. Though most of the deposit is radar bright, it is often bounded by a radar-dark (relative to extant terrain) margin or halo. South of 51°S, much of the deposit is radar dark. The total length of the channel is over 1200 km.

This channel exhibits many characteristics that, on Earth and Mars, can generally be attributed to water erosion. The streamlined hills are remarkably similar in morphometry to water-carved forms (Figure 16). Nevertheless, the direct association with volcanic structures and deposits suggests a volcanic origin. Any endogenetic melts responsible for the outflow must have had immense effusion rates and special compositional properties in order to explain channel landforms that otherwise would be ascribed to flood water origin.

The Longest Channel

The channels of Venus were "discovered" during the Magellan Mission with the recognition, in early September 1990, of the channel in southwest Guenevere Planitia (Figure 5). However, it was found later in the mission that portions of the longest Venusian channel, north of Aphrodite (Figure 11), had been recognized on Venera 15/16 images and mapped as Hildr Fossa [*Kotelnikov et al.*, 1989]. This longest channel originates at 44.5°N, 185°E and terminates at 11.5°N, 167°E in a radar-dark deposit. It is a canali-type simple channel and is the longest channel discovered to date. Its total length (about 6800 km) is longer than the entire Nile River. This channel is developed mostly on lava plains units north of Rusalka Planitia. In spite of local disruption and burial by the later volcanism and cratering, it appears to be a single channel because of consistent trend and the lack of any nearby channels.

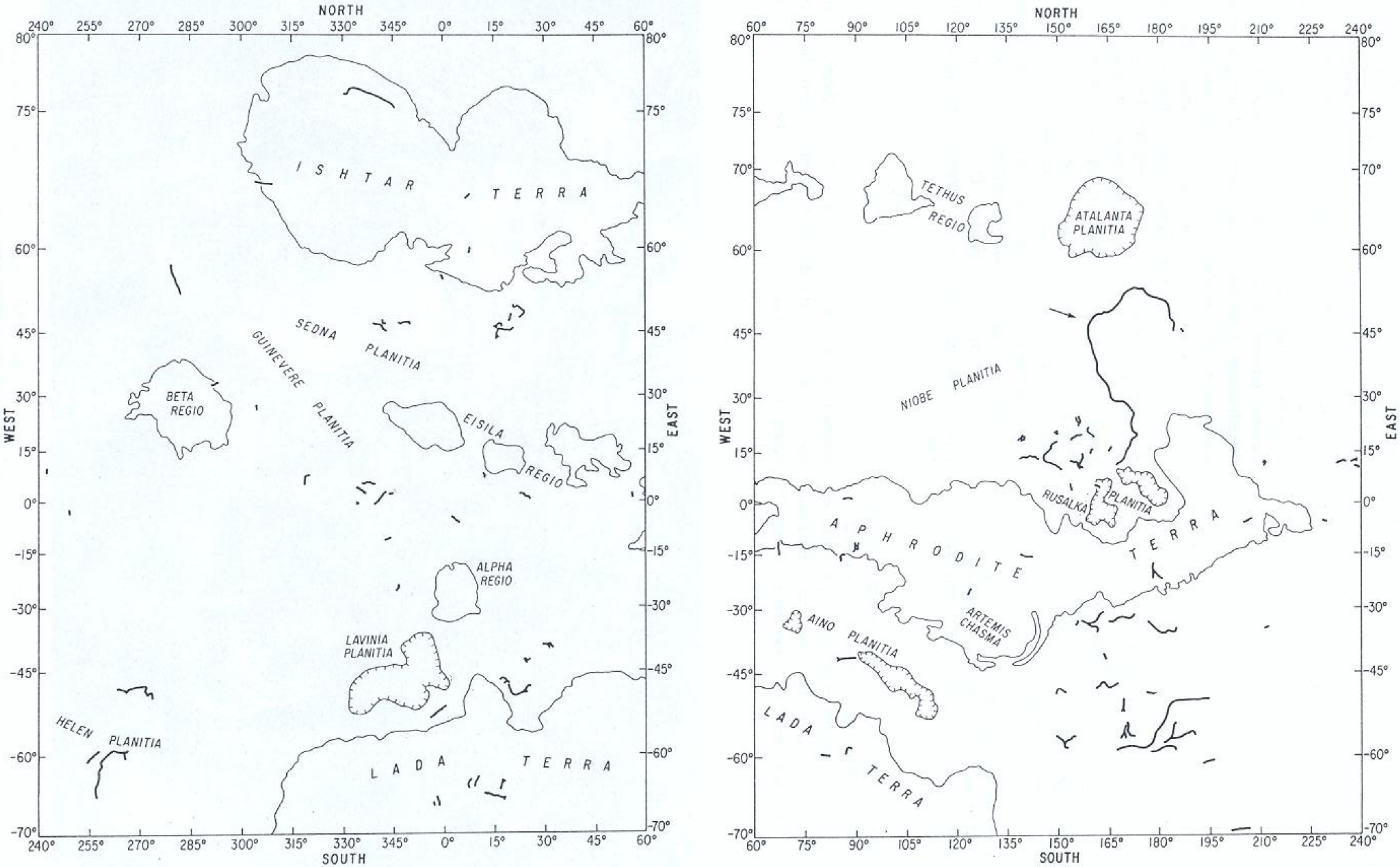

Fig. 11. Global distribution of Venusian channels mapped on Meractor projection. The projection makes it difficult to compare the density of channels. The areas between latitudes 82.5-90°N and 80-90°S are omitted because of lack of image coverage. Areas between 80-82.5°N and 70-80°S are omitted because there are only two channels well defined and long enough to be mapped in these areas. These occur at 81.5°N, 263-275°E and at 74°S, 130°E.

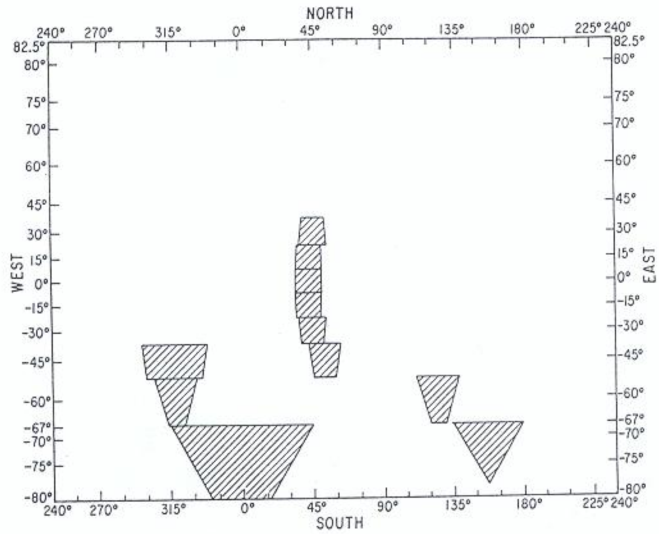

Fig. 12. Image coverage for mapping. Hatched area is lack of image coverage. We also lack image coverage between latitudes 82.5-90°N and 80-90°S (not shown). Some C1-MIDRs (not shown) have gaps which occasionally obscure channels.

The probable channel source is a circular volcanic construct located at 44.5°N, 185°E. The channel is not completely traceable to this source. With a diameter of about 150 km, this construct has a pit crater on its summit. The main part of the channel is sinuous with local reaches of long-wavelength meanders (Figure 17). Channel width (1-3 km) is almost constant over the entire reach but it tends to be narrower near the source and the terminal deposit. Channel depth at 50.4°N, 167.5°E is about 24 m (C. Weitz, personal communication, 1991). At 11.5°N, 167°E in Rusalka Planitia the channel terminates at a radar-dark deposit that probably was emplaced by the material which formed the channel. The channel cuts through plains and tectonic deformation zones, including coronae; so it postdates these features. It is filled by lava flows and disrupted by impact cratering, which it predates. Therefore, this canali-type channel has a potential for determining the age relationship of various geological units over a long distance. Figure 18 shows an approximate topographic profile along the channel constructed from the Pioneer Venus altimetry data. Although the topographic gradient is quite small, the channel floor rises along its flow path. This suggests that tectonic deformations occurred after the channeling process was terminated.

The channel's long length and near constant morphology throughout its entire reach has important implications for the channel-forming fluid properties. The maximum length of lava flows X can be written by the expression [*Head and Wilson*, 1986]

$$X = \frac{D^2 V}{\Lambda k}, \qquad (1)$$

where D is the flow thickness, k is the lava thermal conductivity, V is the flow speed, and Λ is the critical dimensionless Graetz number. The critical Graetz number for Venus is 270,

Fig. 13*a*. Magellan 225 m/pixel mosaic of Ammavaru volcanic complex and the outflow channel in the Lada Terra region of Venus. Total length of the channel, from the source collapse structure to the radar-bright plains deposit, is over 1200 km.

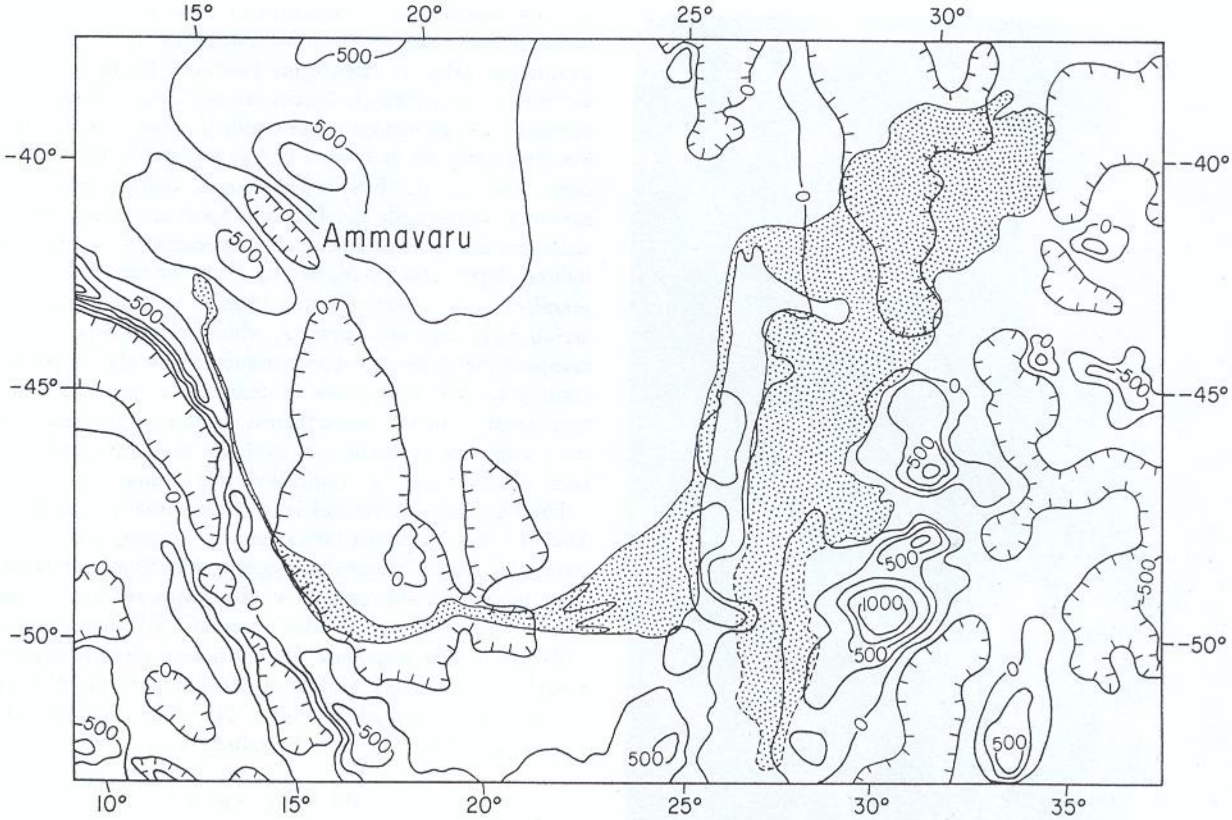

Fig. 13*b*. Topographic map of area imaged in Figure 13*a*. Topography is derived from Magellan altimetry data. The outflow channel and its related depositional plain are shown in gray. A contour interval of 250 m is used with a O datum at a planetary radius of 6052 km.

while that for Earth is 300 [*Head and Wilson*, 1986]. The relationship assumes laminar flow in relatively shallow depth ranges (1-5 m). Taking into account (1) the much higher viscosity of tholeiitic lava (350 P) at its liquidus temperature compared with that of water (10^{-2} P) and (2) the possible range of depth (1-5 m) for laminar flow, we assumed that the maximum flow velocity will not exceed 10 m/s. For this range of parameters and an appropriate thermal diffusivity (10^{-6} m^2 s^{-1}), the maximum distance which lava can travel is about 926 km. More realistically, the deeper flows indicated by channel depths, perhaps 30 m, probably had very high velocities, but cooling would have been much more rapid in a turbulent regime, quickly inducing a transition to laminar flow. Unless there was some effective way of insulating the lava, this result suggests that tholeiitic lava would lose its erosive capacity long before reaching 6800 km. Thus, if turbulent flow erosion formed the canali, a tholeiitic composition is highly improbable. However, the channel-forming lava might have an exotic composition which is discussed in the next section.

CHANNEL-FORMING FLUIDS

The surprising variety of fluvial-like characteristics of Venusian channels, particularly canali-type simple, complex, and compound varieties, has implications for the composition of genetic fluids. The source relationships imply that endogenetic fluids are involved, so our emphasis will be on various kinds of lavas. Nevertheless, the fluvial-like landforms provide critical constraints on the following hypotheses.

Relation of Channel Morphology to Fluid Composition

Volcanic morphologies relate to the physical behavior of erupted lava. The formation of lava channels requires turbulence to permit thermal and/or mechanical erosion. Turbulent conditions occur when $N_R > 2200$, where N_R is the Reynold's number defined as

$$N_R = \frac{\rho V R}{\mu}, \tag{2}$$

where ρ is the fluid density, V is the flow speed, μ is the fluid viscosity (assumed Newtonian), and R is the hydraulic radius (cross-sectional area of channelized flow divided by the wetted perimeter of the bed). For a channel much wider than it is deep and of constant depth D,

$$N_R = \frac{\rho V D}{\mu}. \tag{3}$$

It is expected that for constant D, V would increase as μ decreases and that as μ decreases, flow rates through subsurface conduits and lava discharge rates would increase. Hence equation (2) contains implicit as well as explicit dependencies of flow turbulence on μ. The surface speed of a Newtonian fluid flowing in the laminar regime on an inclined plane (approximating a wide channel) is related to other fundamental parameters [*Turcotte and Schubert*, 1982]:

$$V = \rho g D^2 \sin \alpha / 2\mu \tag{4}$$

Fig. 14. Magellan SAR mosaic (75 m/pixel) of collapsed terrain source area (top) and upper reach of outflow channel. The smaller channels east (right) of the main trough conduit may indicate an early stage of fluid flow prior to collapse of the prominent linear trough.

where α is the angle of channel surface with the horizontal. At low slope angles, typical of rivers, sin α reduces to the slope S, the ratio of vertical fall over a given channel length. Equation (4) does not apply rigorously when channels are being actively eroded by turbulent flows. Nevertheless, substituting this expression in place of V in equation (3) and adding $S = \sin \alpha$ yields

$$N_R = 2\rho^2 g D^3 S / \mu^2 . \tag{5}$$

Equation (5), despite restricted applicability, reveals the influence of viscosity on either (1) promoting stable laminar flow (for high μ) or (2) encouraging turbulent instability (low μ). The dynamical relationships of these parameters for fully turbulent flows are more complex, but equation (5) retains some qualitative validity. Bedforms produced by turbulent fluvial systems and in hydraulic flumes are sensitive to flow speed and somewhat dependent on water depth [*Leeder*, 1982], indicating that bedforms can be related to N_R, and implying an important dependence on μ. First-order channel characteristics such as meander wavelength and braiding habit are dependent on the sediment transport competency of streams, also indicating an indirect dependence on N_R and μ. Thus, we arrive at the guiding premise for this section: that channel and bed morphologies are strongly dependent upon μ, which in turn depends on flow composition. Clearly, other parameters are also important, including surface slope, lava discharge rate, and eruption duration, among others. Nevertheless, in this initial approach to a most complex problem, we evaluate the important effect of lava viscosity and its implications for composition.

The viscosities of various lavas are summarized in Figure 19. The fact that Venusian lava channels in many cases resemble terrestrial fluvial channels suggests that Venusian lavas may have possessed unusually low viscosities relative to basaltic lavas. Figure 20 shows that ultramafic silicate lavas, sulfur, carbonatite, and water are all much less viscous than basalt. Rough interplanetary gravity-scaled comparisons of lava viscosities are presented in Figure 20. The "mobility index," M.I., expressed in cgs units, is defined as

$$\text{M.I.} = \log (\rho \, g / \mu) \tag{6}$$

The mobility index is adapted from solutions to analytical problems involving Newtonian fluid flow, including equation (4). Below, we discuss various possible Venusian lava compositions in some detail.

Silicate Lavas

If Venusian channel-forming lavas were silicate, they must have had ultramafic or highly alkaline mafic compositions (e.g., komatiite, picrite, or olivine nephelinite) to possess high fluidity. Interestingly, the composition of rocks analyzed by Venera 13 [*Surkov et al.*, 1983] is similar to olivine nephelinite. Based on potassium contents, similar rocks may occur at the Venera 8 site [*Keldysh*, 1977]. Olivine nephelinite is commonly erupted in terrestrial hotspot settings and continental rifts. Olivine nephelinite has $\mu \sim 40$ P (measured at the liquidus temperature, and lacking crystals), a factor of 2-20 less than common types of basalt. It is not certain whether this represents a sufficiently low viscosity to explain the most complex outflow channels on Venus. We lack terrestrial examples of channeled landscapes formed by massive discharges of olivine nephelinite or any closely similar lava. It is known that komatiite lavas are capable of efficient thermal-mechanical erosion of channels and that crystallized solids tend to sink to the channel bed rather than be carried in suspension as in most basaltic flows [*Huppert et al.*, 1984]. However, it is generally thought that komatiite flows cool rather rapidly, which is not consistent with the unusually long channels on Venus.

The great lengths of many Venusian lava flows and channels, and their longitudinal continuity of fluvial-like characteristics, seem to indicate a low rate of downstream cooling in addition to low viscosity. Ultramafic and mafic lavas, having liquidus temperatures of 1500-1700°K, usually cool very rapidly. The lava cooling rate on Venus was evaluated by *Head and Wilson*

Fig. 15. Magellan SAR image mosaic (processed at 75 m/pixel) of the "anastomosing reach" of the outflow channel in Lada Terra. This reach begins at the upper left, where the flood overtopped the southern, topographically lower end of the trough. The channel complex width is about 30 km at the left center of the image.

[1986], who concluded that Venusian lavas would cool only ~10% less rapidly than the same composition lava on Earth, allowing ~10% longer flows and channels. Once a lava develops a significant chilled crust, the cooling rate is limited by the rate of thermal conduction through the crust. We find that this rate is lower on Venus due to the temperature dependence of thermal conductivity. However, the calculated cooling rate is only ~25% less on Venus than on Earth. Differences in cooling rates of this order are insufficient to account for the considerable morphological differences between terrestrial and Venusian lava flows and channels.

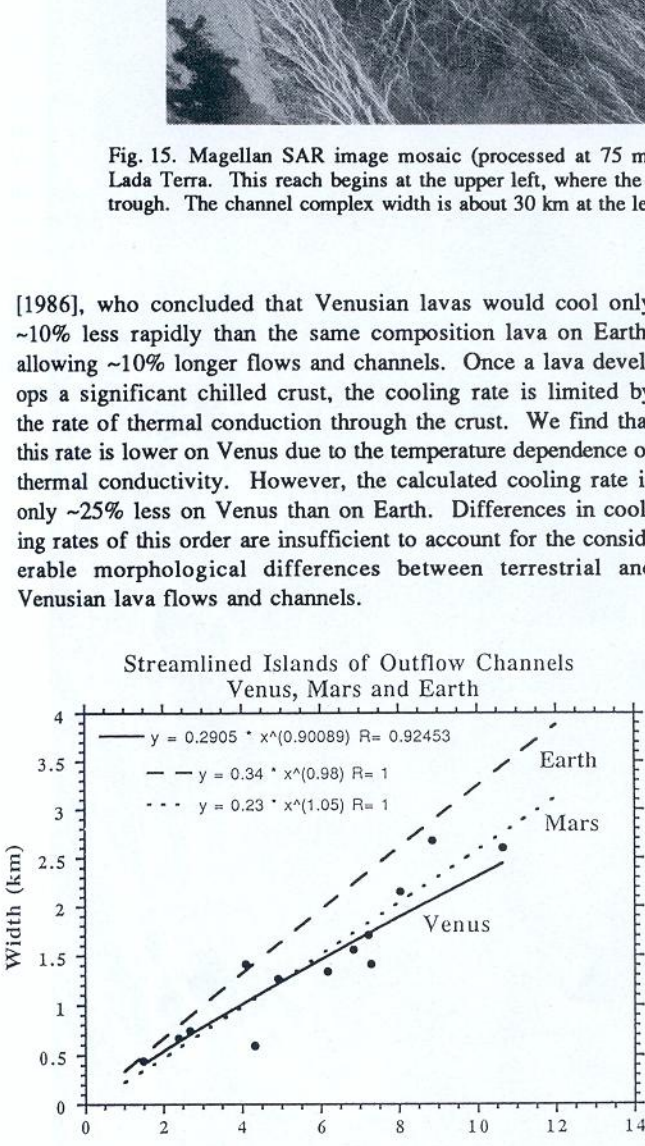

Fig. 16. Comparison of streamlined hill morphology of the outflow channel in Lada Terra with those of Earth (Channeled Scabland) and Mars (Maja and Kasei Valles) cataclysmic flood channels [*Baker*, 1979]. The similarity in geometry suggests that the flows that created this Venusian channel may be similar to those of water under terrestrial or Martian conditions.

We are presently unable to dismiss completely the hypothesis that Venusian outflow channels were eroded by hot silicate lavas, since other variables, particularly magma discharge rates, may have involved quantities outside terrestrial volcanological experience. Indeed, the outflow channel, described above, appears to have involved enormous quantities of lava erupted over short durations. Other long, narrow channels appear to have involved prolonged periods of more modest discharge. In these cases a combination of factors may have prevented rapid cooling. For example, a combination of low μ, high discharge rates, warm atmospheric conditions, and perhaps thermal insulation by rafted scoria or a channel roof (now collapsed) would achieve low cooling rates.

More simply, low lava cooling rates might indicate relatively small temperature differentials between the lavas and the Venusian surface (hence comparatively cool lavas). This would rule out mafic and ultramafic silicate lavas, while the requirement for low μ eliminates siliceous lavas.

Sulfur

Sulfur volcanism dominates the geology of Jupiter's moon Io but is extremely rare on Earth. The rarity of terrestrial sulfur volcanism is in spite of the fact that S is the fifth-most-abundant element in condensible solar matter, and probably also is the fifth-most-abundant element on Earth (after O, Fe, Si, and Mg). Sulfur, like many other volatile elements, is apparently depleted on Earth by a factor of ~4 relative to Cl chondrites due to nebular and accretionary processes. Earth's crust and mantle are depleted by an additional factor of ~75 due to sulfide partitioning into the core. This leaves a trace of S, ~200 ppm, in the crust and mantle. Despite this, sulfurous gases are important volatiles in many terrestrial silicate lavas, and they commonly precipitate sulfurous minerals, including native sulfur, near volcanic vents and fumaroles. These sublimates sometimes remelt, producing sulfur flows variably resembling

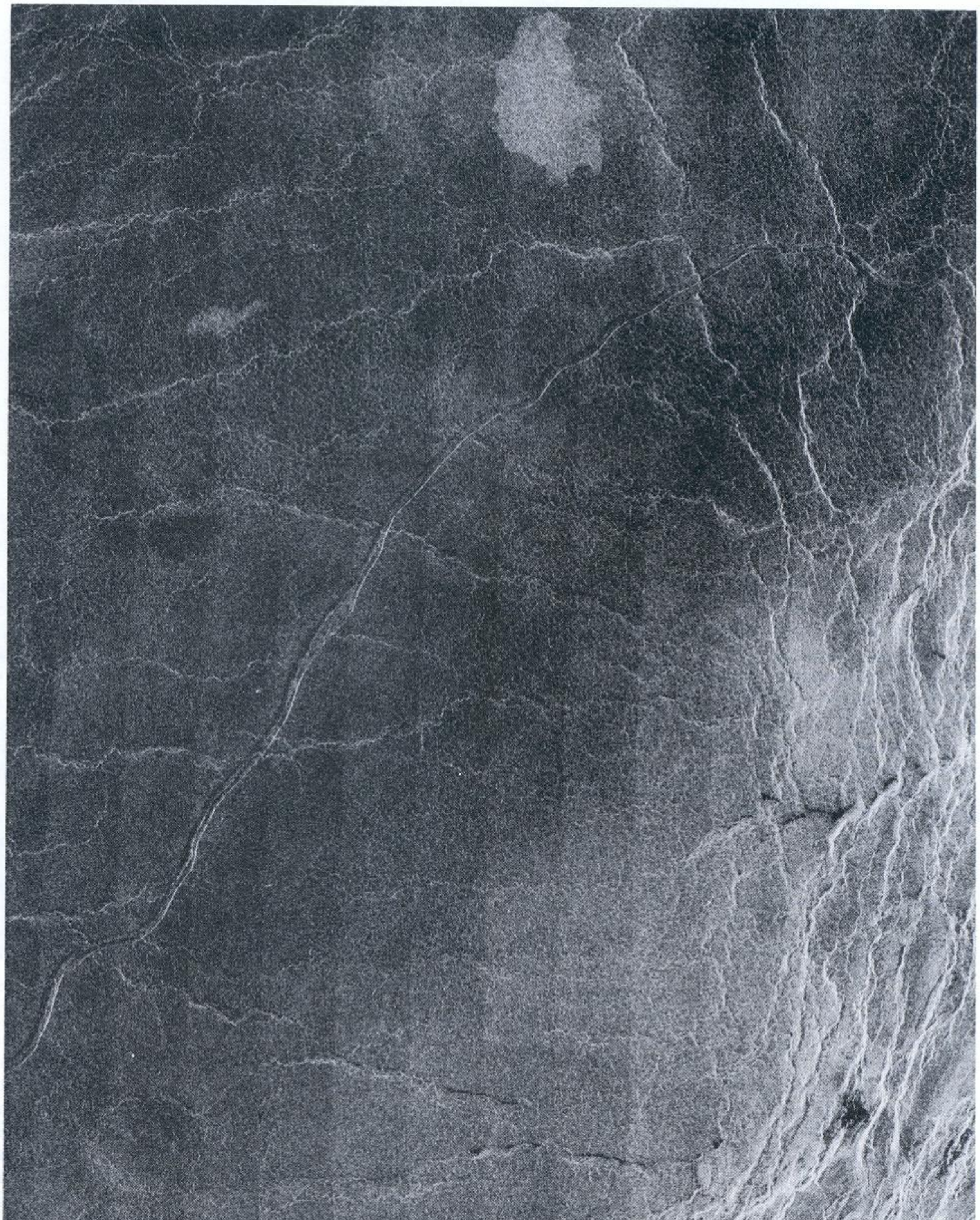

Fig. 17. Meandering reach (50°N, 168°E) of the longest Venusian channel. This canali-type channel cut through various geological units, and it was disrupted by later lava emplacement and tectonic deformation. (C1-MIDR 45N159.)

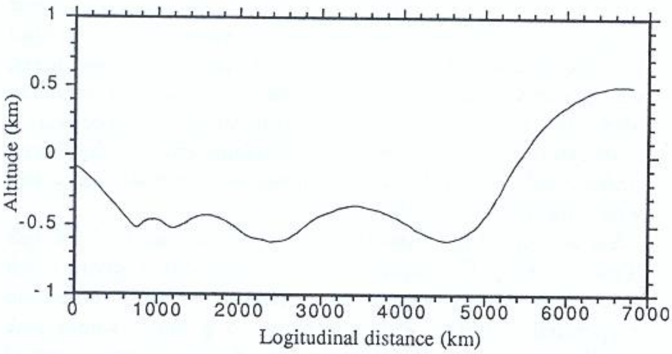

Fig. 18. Topographic profile of longest channel constructed from Pioneer Venus altimetric data. Since the channel-forming lava cannot flow uphill, this profile suggests active tectonic deformation after the channel formation.

pahoehoe and aa basalt [*Watanabe*, 1940; *Colony and Nordlie*, 1973].

Venus probably shares Earth's volatile element depletion. Since Venus has a metallic core, its crust and mantle might also share a similar chalcophile element depletion. However, the Venusian atmosphere contains abundant sulfurous gases, and the Venera landers generally reported several weight percent S in surface samples. One interpretation is that fractionations of sulfides between core and mantle may have been less efficient in Venus than in Earth's interior. If true, the mantle could easily contain an order of magnitude or more S than does Earth's. Potentially, sulfur volcanism could be very important on Venus.

The volcanologically important physical properties of liquid sulfur are reasonably well known. As shown in Figure 17, sulfur exhibits a wide range of viscosities [*Bacon and Fanelli*, 1943], ranging from very waterlike to rather like basalt or andesite. This wide range of μ depends sensitively on temperature and is related to polymerization. Impurities frustrate polymerization in sulfur, resulting in greatly reduced viscosities [*Rubero*, 1964]. Consistent with this viscosity range, the thicknesses of individual terrestrial sulfur flows range from a few centimeters to possibly some tens of meters. Sulfur flows photographed in action resembled streams of water in their dynamical behavior and channeling tendencies [*Watanabe*, 1940].

In contrast to the genesis of sulfur flows on Earth, sulfur magmas on Venus would form by incongruent melting of sulfides such as pyrite at temperatures ~1016°K [*Lewis*, 1982]. Pyrite yields approximately one-fourth by mass sulfur liquid plus three-fourths pyrrhotite. The residual solid pyrrhotite melts to a sulfide liquid of roughly its own composition at a temperature near 1468°K, comparable to or slightly below the solidus of dry peridotite. Liquid sulfur has a density of 1.60 g cm^{-3} at 723°K [*Tuller*, 1954] and would readily extrude. Sulfur erupted near 1000°K would actually be less viscous than water at ordinary temperatures (Figure 17). Analogous to water on most parts of Earth, and quite unlike silicate and carbonate lavas, sulfur would not crystallize on Venus since the freezing point of pure S is 388°K. Erupted sulfur would pond in depressions and percolate into any available pore spaces. If the lava flows far enough, it might cool to Venusian ambient temperatures of ~750°K. The viscosity of the cooled sulfur would increase, but would remain less than 1 P under all circumstances.

Although well below the critical point (1313°K, 200 atm

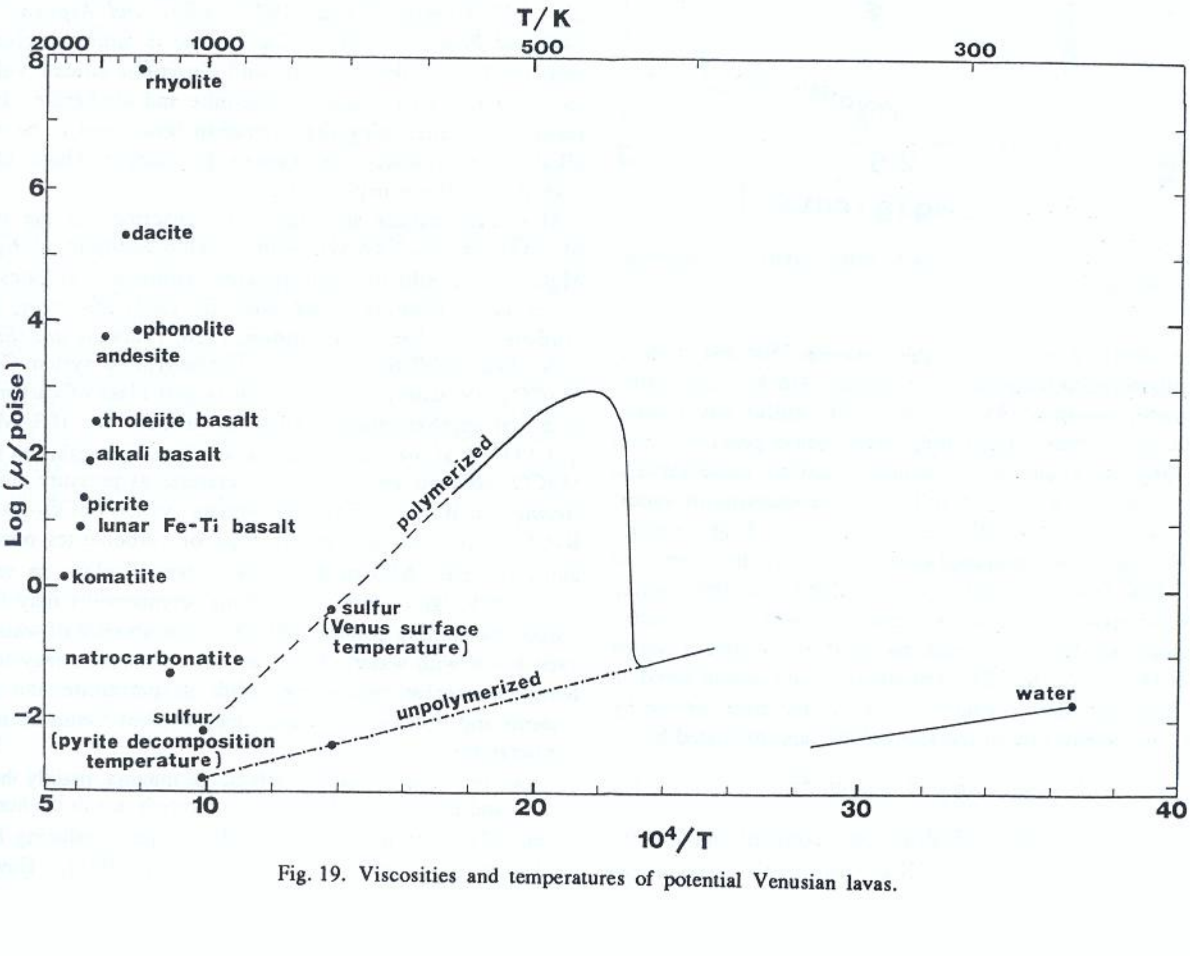

Fig. 19. Viscosities and temperatures of potential Venusian lavas.

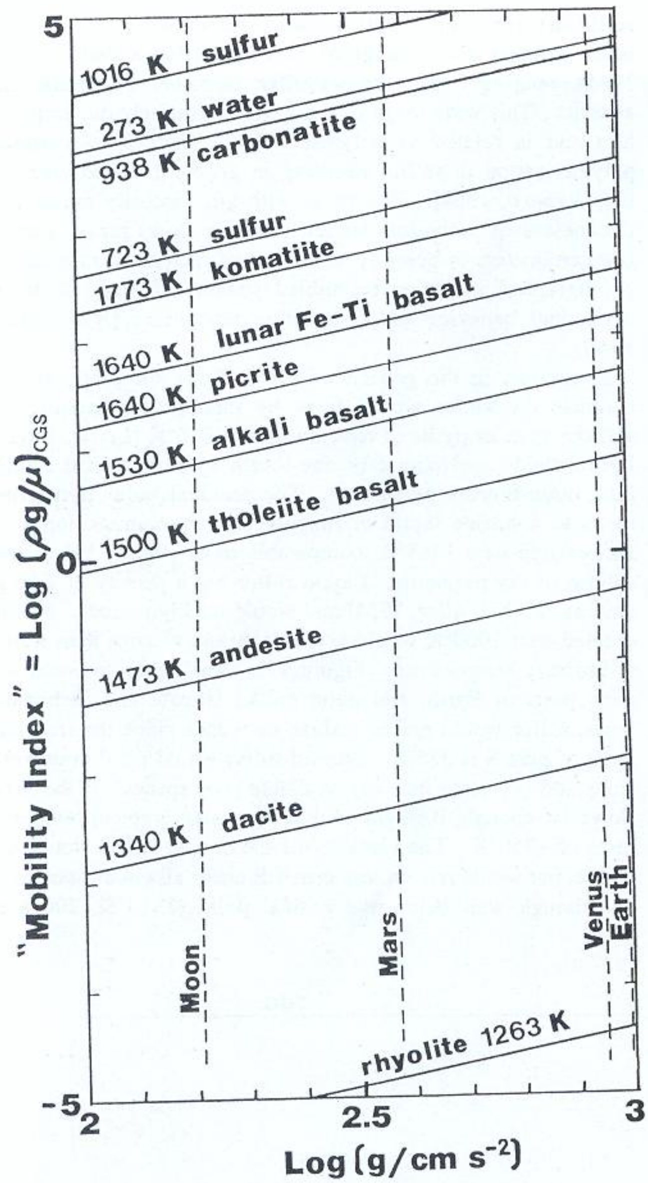

Fig. 20. Variation of mobility index with gravity for potential channel-forming fluids.

[*Meyer*, 1976]), S is rather volatile between 750° and 1016°K. At the dissociation temperature of pyrite, 1016°K, liquid sulfur has a vapor pressure ~25 bars; at 750°K, sulfur has a vapor pressure of 1.5 bars. Therefore, sulfur would generally erupt quiescently on Venus, but it would evaporate quite rapidly, especially at first while it is still hot. The enthalpy of vaporization of S is ~3.3×10^9 ergs g^{-1}, and the heat capacity ~1.4×10^7 ergs g^{-1} K^{-1} averaged over the temperature interval of 750-1016°K [*Tuller*, 1954]. In the limiting case that cooling occurs entirely by evaporative enthalpic loss, liquid sulfur would lose two-thirds of its mass to vapor by the time it cooled from 1016° to 750°K. The remaining liquid would pond in depressions and slowly evaporate, the evaporation driven by the thermal radiant flux of the atmosphere, approximated by

$$F = \sigma T^4 = 1.8 \times 10^7 \text{ ergs cm}^{-2} \text{ s}^{-1} \quad (7)$$

where σ here is the Maxwell-Boltzmann constant and *T* is the temperature. Evaporation at 750°K of a sulfur lake could reduce the lake level at a maximum rate ~2 m d^{-1}, but somewhat lower evaporation rates are likely since the atmosphere in contact with the lake would have a finite sulfur humidity. Nevertheless, we can expect that a sulfur lake would last some days to months (depending on its depth), after the influx of liquid had ceased. It is therefore reasonable on thermodynamic grounds that liquid sulfur could exist on Venus over timescales normally associated with catastrophic flooding events.

Sulfur formed by dissociation of pyrite contains ~1-2% FeS [*Lewis*, 1982]. This liquid is initially saturated in pyrite which would immediately begin to precipitate as the flow cooled and evaporated. Pyrite, with a density ~5 g cm^{-3}, would sink rapidly through the low-viscosity liquid and become a part of the bedload. The pyrite might tend to react with Ca-bearing crustal rocks, forming anhydrite [*Fegley and Treiman*, 1992], although thick channel and lake bed deposits of pyrite may be effectively isolated from and unable to react with the crust. The evaporated sulfur would also eventually oxidize and react globally with the crust. The quantity of sulfur released by a single massive outflow-channel-forming event (~5×10^{18} g) would add ~20 ppm by mass SO_2 (after oxidation) to the atmosphere, compared to ~200 ppm reported by the Venera landers.

Carbonate Lavas

Carbonatite is widespread and locally abundant on Earth but is rare compared to basaltic and many other silicate magmas. Carbonatite volcanism occurs in certain shield areas, on hotspots, and along the East African Rift. Carbonatite is mantle-derived, usually originating by very low degrees of partial melting of carbonated mantle peridotite and/or by immiscible segregation of carbonate fluids from mantle-derived alkaline silicate magmas, especially nephelinite [*Cooper et al.*, 1975; *Hamilton et al.*, 1979; *LeBas and Aspden*, 1981; *Bell and Peterson*, 1991]. Carbonatite is almost exclusively associated with alkaline mafic and ultramafic silicate volcanic rocks such as alkali basalt, nephelinite and kimberlite. In this respect it is interesting that Venusian lavas tend to be highly alkaline, particularly the Venera 13 sample which closely resembles olivine nephelinite.

Most carbonatites are fairly well described in the system $MgCO_3$-$CaCO_3$-Na_2CO_3, with variable additions of K_2CO_3, MgO, mafic silicates, phosphates, chlorides, sulfates, and water [*Von Knorring and DuBois*, 1961; *Dawson*, 1962; *DuBois et al.*, 1963; *Vartiainen*, 1980; *Treiman and Essene*, 1984; *Bell and Peterson*, 1991]. The anhydrous system $CaCO_3$-$MgCO_3$ adequately represents the largest class of carbonatites to a first approximation and has an eutectic near 10% $MgCO_3$ and 1373°K at pressures of a few kilobars, increasing to higher $MgCO_3$ contents and higher temperatures as pressure increases [*Irving and Wyllie*, 1975]. The ternary system $CaCO_3$-Na_2CO_3-K_2CO_3 represents a common type of carbonatites occurring along the East African Rift; this system displays an eutectic near 938°K (at 1 kbar). Additional components may further reduce the melting point to ~850°K in the absence of water, and even lower with water. Thus carbonatite magmas may form at temperatures far below the solidi in peridotite and basalt systems and just slightly higher than ambient Venusian surface temperatures.

Vapor pressures of calcic carbonatite magma, mainly the sum of CO_2 and H_2O partial pressures, commonly are in the hundreds of bars [*Treiman and Essene*, 1984], often producing highly explosive eruptions [*Bell and Peterson*, 1991]. However, quiescent eruptions of sodium carbonatite sometimes form pahoehoe and aa flows [*Dawson*, 1962]. The probable anhydrous chemistry of Venusian carbonate lavas and the high surface pressure would tend to encourage similar quiescent eruptions, although explosive eruptions may also occur.

Treiman and Schedl [1983] estimated the density of carbonatite magma as ~2.2 g^{-3}. Few laboratory or field data bear directly on the rheology of molten carbonates, with the important exception of Na_2CO_3, which is characterized by μ ~3 cp at its melting point (about twice that of liquid water at 273°K; *Treiman and Schedl* [1983], based on work by *Janz and Saegusa* [1963]). Additional components would lower the melting point of the mixture, probably increasing μ at the eutectic point. Hence, carbonate mixtures may be more viscous than estimated by *Treiman and Schedl* [1983], but their conclusion that carbonate magmas should have very low viscosities relative to silicate magmas is almost certainly valid in all instances. An upper limit ~1 P is obtained for a multicomponent natrocarbonatite, estimated by extrapolating μ of pure Na_2CO_3 liquid [*Janz and Saegusa*, 1963] to a eutectic temperature ~850°K. A viscosity closer to 0.05 p as estimated by *Treiman and Schedl* [1983] is considered more likely in view of nonideal effects on μ in mixed carbonates [*Janz and Saegusa*, 1963].

Water

Liquid water, with its low μ, would be attractive in explaining the very fluvial-appearing nature of many Venusian lava channels. However, stability of liquid water would require Venusian temperatures <580°K (for 90 bars atmospheric pressure), ~170°K lower than present. Furthermore, water is unattractive in view of the exceedingly dry environment of Venus today, the absence of independent geomorphic evidence for ancient activity of liquid water, and the difficulty in storing or eliminating large amounts of ancient water.

REGIME RELATIONSHIPS

Following their discovery in 1972, the widespread channels and valleys of Mars were hypothesized to have been carved by nearly every conceivable fluid [*Baker*, 1985]. In this paper we suggest multiple hypotheses for the fluid-erosive origin of the Venusian channels and valleys. The fluvial-like landforms seem to require prolific discharges of low-viscosity fluids that remained liquid for very prolonged time periods.

Another remarkable observation, that can only briefly be noted in this preliminary summary, is the apparent regime behavior of the active Venusian channels. As in terrestrial meandering rivers (Figure 10), Venusian canali-type channels show the general relationship

$$\lambda = 4.7\, R_m\ , \qquad (8)$$

where λ is the meander wavelength and R_m is the radius of curvature expressed in similar units [*Leopold and Wolman*, 1957]. This relationship derives from dependencies of both λ and R_m on the channel geometry, particularly the width associated with a channel-forming discharge [*Leopold et al.*, 1964]. Meander wavelength scales to bankfull width W_b approximately as follows [*Williams*, 1988]

$$\lambda = 7.5\, W_b^{1.12}\ . \qquad (9)$$

Bagnold [1960] attributes this scaling to the development of

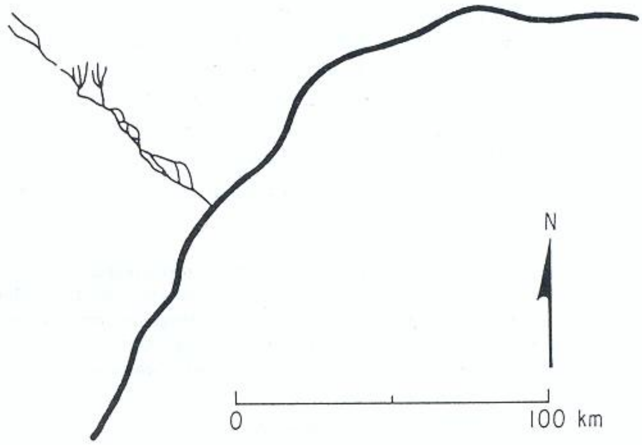

Fig. 21. Transition of a canali-type channel to a complex anastomosing pattern. Sketch map of a region in Guenevere Planitia, 8°N, 332°E.

geometries of minimum resistance to flow, minimizing turbulence at bends and establishing a quasi-equilibrium between flow and geometry. Such channels are self-formed, adjusting their shapes to the processes associated with them.

Many meandering canali reaches (Figures 5, 6, and 17) show a general consistency with equations (8) and (9), although further study is necessary on this point. Moreover, there are examples of abrupt transition from simple, canali-type morphology to complex, anastomosing patterns (Figure 21). Such transition is also common in rivers, wherein slope and discharge define two stable regimes of behavior [*Leopold and Wolman*, 1957; *Schumm*, 1977]. Meandering occurs at relatively low combinations of these two variables, and braiding occurs at high combinations. A distinct threshold, usually a slope change [*Schumm*, 1977], generally results in transitions of one morphology to another.

The streamlined hill formation at high-energy, high-discharge conditions (Figure 16) is another direct parallel to the sequence of behavior exhibited by the interaction of water and its channel boundary materials. If water is not invoked to explain these channels, as seems prudent from other arguments, then these remarkable parallels to aqueous behavior require alternative explanation.

The longest Venusian channels seem to be relics of regime processes, arrested in time as in the case of terrestrial fluvial paleochannels [*Schumm*, 1977]. Moreover, they have been deformed since their development (Figure 18). Thus their slope relationships may be useful in establishing the extent of neotectonic deformation.

CONCLUSIONS

There are several possibilities for low-viscosity, channel-forming fluids on Venus, including ultramafic or highly alkaline mafic silicates, carbonatite, and sulfur. The latter two are attractive since they have very low melting points and water-like viscosities and would readily explain the great lengths, fluvial-like aspects, and longitudinal uniformity of channels. Ultramafic or alkaline mafic silicate lavas are attractive since the surface as reported by the Venera and Vega landers is composed primarily of mafic silicates, and highly potassic rocks occur at two of several landing sites. Water cannot be ruled out by the landform features, but the theoretical implications of an aqueous origin are so contrary to current understanding of Venus that we have not pursued them further.

At the present state of explanation we seem to have discovered a complementary relationship in solar system surface water hydrology. On the icy satellites of the outer solar system, surface water behaves like lava, but on Venus, lava behaves like water.

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