Reports

Geomorphic Degradations on the Surface of Venus: An Analysis of Venera 9 and Venera 10 Data

Abstract. *On the basis of the physical and chemical measurements made on the surface of Venus and transmitted back to Earth by the Soviet automatic landers Venera 9 and Venera 10, a geomorphically inactive environment should be expected. An analysis of the television photographs reveals, however, that at least two processes of degradation occur. One operates on a scale of decimeters to meters and is responsible for the fracturing of a layered source rock and the subsequent downslope movement of the fragments. Mass-wasting, perhaps activated by venusian quakes or by unknown geological processes, is likely to be the agent. Another geomorphic degradation process occurs on the scale of a centimeter or less and is responsible for the rounding of edges and the pitting of rock surfaces. The agents of this process are not known, but atmospheric action, perhaps in connection with volcanic episodes, may be the cause. From a geomorphic point of view, the landscape of the Venera 9 landing site can be considered young and that of the Venera 10 landing site, mature.*

In October 1975, the Soviet automatic landers Venera 9 and Venera 10 landed on the surface of Venus (*1*). In addition to television pictures, the following data were transmitted back to Earth. Temperature and pressure were essentially the same at both landing areas (*2*), 730° to 740°K and 85 to 91 kg/cm^2, respectively, an indication that the areas are at almost the same elevation. The wind velocity, measured by an anemometer at about 1 m above the surface, was 0.5 to 1 m/sec at both sites (*3*). The same wind velocity is deduced from Doppler effects at an altitude of 30 to 40 m above the surface (*4*). Photometric profiling (*5*) at an elevation of 25 to 45 km indicates that the ratio of the volumetric contents of H_2O to CO_2 is about 10^{-3}. The gamma spectroscopic measurements (*6*) indicate the following composition for the material under Venera 9: 0.47 ± 0.08 percent potassium, 0.60 ± 0.16 part per million (ppm) of uranium, and 3.65 ± 0.42 ppm of thorium. In the case of Venera 10, the results are 0.30 ± 0.16 percent potassium, 0.46 ± 0.26 ppm of uranium, and 0.70 ± 0.34 ppm of thorium. These values are similar to those found for basalts on Earth. The densitometer of Venera 10 (*7*) gave a density of 2.8 ± 0.1 g/cm^3 for the material under the instruments. As will be discussed below, the densitometer was located on a hard rock. The measured density is comparable with that of most hard rocks on Earth and on the moon.

The conditions on the surface of the planet (*8*) are such that little geomorphic activity should be expected. The winds are very gentle, and the amount of water vapor is very low. Even the most common geomorphic process on the surface of Earth's moon, meteoritic and micrometeoritic impact, is likely to be severely curtailed on Venus because of the thick atmosphere. It has been calculated that no meteorite smaller than 30 m (irons) or 60 m (stones) can penetrate the venusian atmosphere (*9*). However, the photographs clearly show the presence of at least two geomorphic degradational processes.

The panoramic television cameras (*1*) have a nominal field of view of 40° by 180°, looking down 50° from the spacecraft's equator, so that the center of the pictures shows the ground in front of the craft and the sides show progressively higher views until the horizon appears at the extremities. The original photographs, widely distributed by the press, were interrupted by vertical bands corresponding to the intervals of time in which other information was transmitted to Earth. Several types of computer enhancement were used by the Institute of Problems of Translation of Information, Academy of Sciences of the U.S.S.R., involving different degrees of tone darkness, contrast, and perspective (*10*) to produce the photographs shown here. Figure 1 shows the Venera 9 and Venera 10 pictures with vertical lines eliminated, and Fig. 2 with the perspective changed to a more familiar view. The bottom supporting ring of the spacecraft is visible in the bottom center of the photographs. The rakelike instrument in the bottom right is a gamma densitometer; the transversal unit is approximately 40 cm long. The segmented object in the middle of the Venera 10 photograph is the discarded view-port cover (10 by 40 cm).

Venera 9 came to rest on the surface of Venus on a rock-strewn field having a slope of approximately 15° to 20° (*11*). The gradient of the downslope is approximately toward the 8 o'clock direction (Figs. 1 and 2). The boulders appear to be larger in the horizontal dimension, up to 50 or 70 cm, than in the vertical dimension, 15 to 20 cm. Most of the boulders have sharp edges; at least two of them show a sharp point. At least three boulders show evidence of layering approximately in an attitude parallel to the upper surface of the boulders.

The head of the densitometer lies on two boulders. From preflight tests (*12*) we know that the densitometer head, with a mass of about 2 kg, strikes the target with a velocity of about 7 m/sec, comparable to the blow of a sledge hammer. The effects of the blow are difficult to determine from the photograph. Either there was no effect, or the boulder to the left of the densitometer was broken by the blow. In either case, it appears that the boulders are hard rock.

The boulders lie on a darker matrix, composed for the most part of particles smaller than the resolution of the camera. Some centimeter-sized fragments are visible. Most of the boulders appear to lie flat on the matrix, but at least two are at an angle and a few are partially buried.

The horizon lines are visible on both sides. Features which must be boulders are apparent on the horizon lines, an indication that they are near, no more than a few tens of meters from the spacecraft, and are caused by local topography.

Venera 10 came to rest on a plain composed of dark material, within which there are "islands" of hard material of relatively higher albedo. These islands can be described as outcrops. No evidence of any effect caused by the impact of the densitometer with the surface is visible; thus the outcrop is hard. The surface of the outcrops is smooth on a decimeter scale and pitted on a centimeter scale. Except for two cases, the edges are blunt and rounded. The pits on the surface seem to be filled with material similar to the matrix and, in many cases, appear to be aligned in chains. Several fractures occur on the outcrops. The dark material at the Venera 10 landing site has the same appearance as the fine material at the Venera 9 landing site.

Horizon lines appear on both sides of the photograph and lack features. Thus it is thought that the horizon is distant from the spacecraft.

The photographs may be interpreted in the following way. The sharpness of the edges and the lack of rounding of the boulders at the Venera 9 landing site indicate that the boulders were produced by the breaking of originally hard rocks. The slablike appearance together with the layering visible on some of the boul-

Fig. 1. Panoramic photographs taken by Venera 9 (upper photo) and Venera 10 (lower photo). Computer enhancement consisted of the elimination of vertical lines, a slight increase in contrast, and a cosmetic increase in resolution. The enhancement was achieved by the Institute of Problems of Translation of Information, Academy of Sciences of the U.S.S.R.

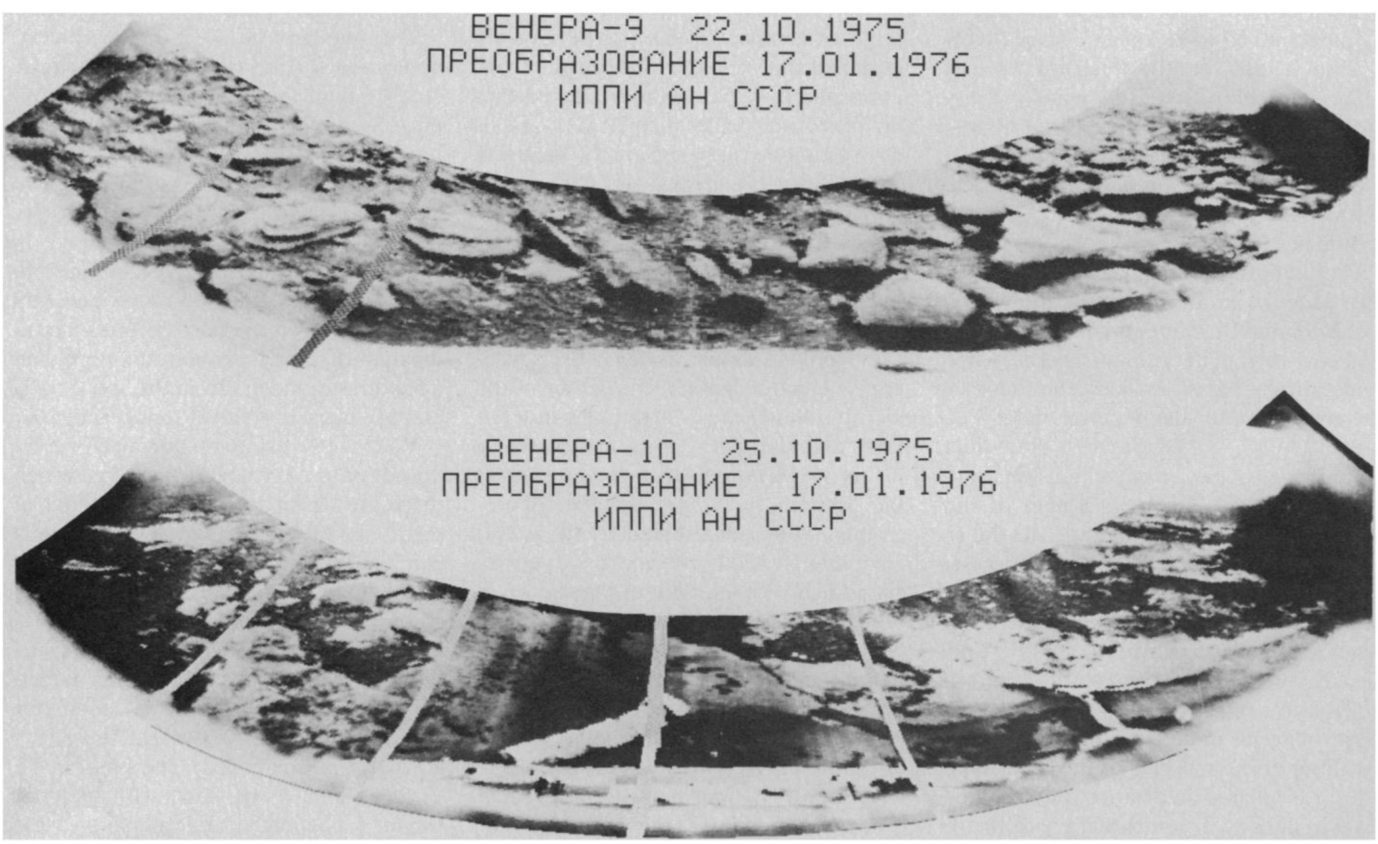

Fig. 2. Panoramic photographs as in Fig. 1, with the perspective changed to a more familiar view by the Institute of Problems of Translation of Information in collaboration with the Central Research Institute of Geodesy, Aereal Surveying, and Cartography.

ders suggest that the source rock may have been layered. In addition, the boulders are on a slope and one may postulate that the source rock is somewhere uphill from the area photographed. A process of degradation is, or was, clearly operating in this area. Because of the size, this process can be referred to as the decimeter-scale degradation.

Another process of degradation must also be postulated to account for the pitted surfaces and rounded edges of the outcrops at the Venera 10 landing site. Because of the scale, this process may be referred to as the centimeter-scale degradation. From a geomorphic point of view, the landscape of the Venera 10 landing site is more mature than that of Venera 9 landing site.

It is difficult to speculate on the nature of the two degradational processes. The decimeter-scale degradation is likely to be mass-wasting, but in the absence of liquid water it is hard to visualize the activating agent. If future landers find high seismic activity, venusian quakes could be the agent.

The centimeter-scale degradation is even more puzzling. The gentle winds and the inert atmosphere cannot be the agents, unless active chemical compounds are present in as yet undetected amounts. Sporadic inputs from volcanic events, either chemically or dynamically active, may also be possible (*13*).

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References and Notes

1. A. P. Vinogradov, C. P. Florensky, A. T. Basilevsky, A. S. Selivanov, *Dokl. Akad. Nauk SSSR* **228**, 570 (1976); *Pis'ma Astron. Zh.* **2**, 67 (1976) (in Russian).
2. V. S. Avduevsky *et al.* (preprint Pr-278, Institute of Space Research, U.S.S.R. Academy of Sciences, Moscow, 1976), p. 13 (in Russian).
3. V. S. Avduevsky *et al.*, *Dokl. Akad. Nauk SSSR* **229**, 52 (1976) (in Russian).
4. N. M. Antzibor *et al.* (preprint Pr-278, Institute of Space Research, U.S.S.R. Academy of Sciences, Moscow, 1976), p. 14 (in Russian).
5. V. I. Moroz, N. A. Parfentyev, N. V. Sanko, V. S. Zhegulev, L. V. Zasova, E. A. Ustinov, *ibid.*, p. 15.
6. Yu. A. Surkov, F. F. Kirnozov, V. N. Glazov, G. A. Fedoseev, *ibid.*, p. 11.
7. Yu. A. Surkov, F. F. Kirnozov, V. K. Khristianov, V. N. Glazov, V. F. Ivanov, B. N. Korchuganov, *ibid.*, p. 10.
8. L. B. Ronca and R. R. Green, *Astrophys. Space Sci.* **8**, 59 (1970).
9. M. E. Tauber and D. B. Kirk, *Icarus* **28**, 351 (1976).
10. B. V. Nepoklonov, A. S. Selivanov, M. K. Naraeva, G. A. Leikin, L. P. Yaroslavsky, M. A. Kronrod, Yu. S. Tyuflin, E. P. Alexashin, in *Surfaces of Venus and Mars* (Nauka, Moscow, in press) (in Russian).
11. C. P. Florensky, A. T. Basilevsky, A. A. Pronin, G. A. Burba, in *ibid.*; C. P. Florensky, A. T. Basilevsky, A. A. Pronin, paper presented at the 19th session of the Committee on Space Research (COSPAR), Philadelphia, 1976.
12. Y. A. Surkov, F. F. Kirnozov, V. K. Khristianov, B. N. Korchuganov, V. N. Glazov, V. F. Ivanov, paper presented at the 19th session of COSPAR, Philadelphia, 1976.
13. Work is in progress to develop geochemical models to explain these results (C. P. Florensky *et al.*, *Geol. Soc. Am. Bull.*, in press).
14. This research was conducted during an exchange program between the U.S. National Academy of Sciences and the Academy of Sciences of the U.S.S.R.
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15 October 1976; revised 11 January 1977

Determining the General Circulation of the Oceans: A Preliminary Discussion

Abstract. *The classical oceanographic problem of deducing the unknown constant in the dynamic method—the problem of the "level of no motion"—may be treated as a geophysical inverse problem. The unknown "barotropic" velocity may be chosen to satisfy an arbitrary number of conservation laws, subject to perfect geostrophic balance and with explicit use made of the relative errors in the observations. The solution obtained is one of minimum energy. A western North Atlantic region is used to demonstrate the power of the method.*

Most knowledge of the general circulation of the world oceans is based on the classical dynamical method. Under the assumption of geostrophic balance, one computes the vertical shear of velocity from observed horizontal gradients in the mass field. The major difficulty with this method is that there is a missing constant of integration. This missing constant, the barotropic velocity, cannot normally be determined by direct means, and over the years oceanographers have developed a variety of ad hoc methods (*1*) for determining it as a function of position. Many of these methods are based on the idea of a "level of no motion"—the assumption that somewhere at depth there is a level (pressure surface) where the velocity vanishes. If there is such a level and it can be determined, then the missing constant of integration is known and the complete flow field computed. Most such methods are based on sometimes plausible, if imprecise and arbitrary, assumptions about the behavior of chemical tracers. None of them can be considered well established or very convincing. Hidaka (*2*) attempted to determine the barotropic flow directly by conserving heat and salt within a volume of ocean. He was criticized by Defant (*3*), who showed the problem to be ill posed and hence unstable. Stommel (*4*) used specific dynamical ideas to determine the meridional component of the barotropic flow, but with mixed results.

Worthington (*5*) has recently attempted a complete synthesis of the general circulation of the North Atlantic. He nearly conserves (some small property exchange does occur) total heat and salt at various levels in the ocean and constrains the circulation to absorb supposedly known amounts of water from various sources (such as the Norwegian Sea). To close his circulation, Worthington violates the assumption of geostrophy. If one seeks the reason for this violation it is seen to follow from his arbitrary selection of a level of no motion.

In this report I show that (i) one may require that geostrophic balance be exact, (ii) conservation of an arbitrary number of properties may be required to within any predetermined accuracy, (iii) there is an infinite number of flow fields that will satisfy (i) and (ii), (iv) out of the infinite number of solutions one may rationally choose a unique field based on a simple dynamical principle, and (v) the formalism permits one to understand the relationship between the flow field actually chosen and all other acceptable fields and the degree to which the observations actually constrain the flow.

The burden of this report is that this problem is an excellent example of one for which the formalism of geophysical inverse theory (*6–8*) is suited. To be specific, I consider the sections of hydrographic stations shown in Fig. 1. These were obtained by Worthington on the R.V. *Atlantis* in 1955. The stations are such that they nearly confine a volume of ocean including the Gulf Stream. With the ocean in a (presumed) steady-state condition, one expects that, on the average, there will be conservation of mass within this volume, and that to within an excellent first approximation individual water masses will also be conserved as long as they are not in contact with the atmosphere. There are $M = 43$ usable station pairs in Fig. 1. Figure 2A shows the geostrophic velocity field for the sections with the level of no motion assumed to be at the sea floor. This choice implies that 20 sverdrups (20×10^6 m^3/sec) more water leaves the volume than enters it.

Let v_{ij} be the known baroclinic velocity at pressure level i between station pair