7. Methods for obtaining the SPM and dissolved oxygen values in Table 1 are described in M. A. Franson, Ed., *Standard Methods* (American Public Health Association, Washington, D.C., ed. 14, 1976); DOC was determined according to the method of D. Menzel and R. Vaccaro, *Limnol. Oceanogr.* **9**, 138 (1964); chlorophyll a was measured according to the method of J. D. H. Strickland and T. R. Parsons, *Fish. Res. Board Can. Bull. 167* (1972); ATP was measured according to the method of O. Holm-Hansen and R. C. Booth, *Limnol. Oceanogr.* **11**, 510 (1966); and POC and PON were measured by means of a Perkin-Elmer model 240 elemental analyzer. Particulate organics are functionally defined as those materials that are retained by a Gelman type-A glass fiber filter; dissolved organics are defined as those materials that pass through such a filter. Light extinction was measured at 400 nm.
8. T. Casadevall, personal communication.
9. R. C. Wissmar, unpublished data.
10. Lakes outside the blast zone had a "normal" diversity of phytoplankton for the region (*6*). For example, McBride Lake was dominated (95 percent of 7373 total cells per milliliter) by unidentifiable unicellular blue-green and flagellated green algae. Other taxa included *Sphaerocystis*, *Scenedesmus*, *Asterionella*, *Monoraphidium*, *Dinobryon*, *Synedra*, *Chroomonoas*, *Aphanizomenon*, and *Lyngbya*. Some blast zone lakes had algae but less than McBride (that is, 878 total cells per milliliter in Fawn Lake and 250 in Ryan Lake). Fawn and Ryan lakes had the most diverse algal communities in the blast zone (*Chroococcus*, *Cryptomonas*, *Mallomonas*, *Chlorella*, *Chlamydomonas*, *Stephanodiscus*, *Euglena*, *Lyngbya*, and *Gymnodinium* in Ryan Lake). Spirit Lake contained *Chroomonoas*, *Synura*, *Melosira*, and unidentified blue-green colonies. The debris flow pond in the pyroclastic flow had a dense green bloom of *Oocystis* and *Achnanthes*. West Castle Lake contained *Cryptomonas*, an unidentified green alga, and dinoflagellates. Algae were not found in samples from South Coldwater Lake. Invertebrates of the lake water columns were represented by limnetic crustaceans, rotifers, and insects. For example, Merrill and McBride lakes contained crustaceans (*Diaptomus*, *Ceriodaphnia*, *Daphnia*, and *Bosmina*), rotifers (*Polyarthra*, *Hexarthra*, *Kellicottia*, and *Conochilus*), and insect larvae (*Chironomidae*). Animals in blast zone lakes were sparse. Fawn and Ryan lakes had cyclopoid copepods, *Diaptomus*, ostracods, *Kellicottia*, and chironomid larvae. Boot, Panhandle, Venus, and Hanaford lakes contained only copepods and chironomids. Spirit Lake contained rotifers (*Keratella*, *Filinia*, and *Hexarthra*), in distinct contrast to the diverse zooplankton community on 4 April 1980 (*Bosmina*, *Daphnia*, *Diaptomus*, cyclopoid copepods, and rotifers *Asplanchna* and *Kellicottia*). West Castle and South Coldwater lakes were devoid of invertebrates. Protozoans (ciliated and nonciliated) were observed in most of the lakes.
11. J. W. M. Rudd and R. D. Hamilton, *J. Fish. Res. Board Can.* **30**, 1537 (1973).
12. Method of J. E. Hobbie, R. T. Daley, and S. Jaspers [*Appl. Environ. Microbiol.* **33**, 1225 (1977)].
13. Viable bacteria were enumerated by spread plating on CPS culture medium [J. G. Jones, *J. Appl. Bacteriol.* **33**, 679 (1970)].
14. F. Ruttner, *Fundamental Limnology* (Univ. of Toronto Press, Toronto, 1965).
15. Coliform bacteria were counted on 11 September 1980 [M. A. Franson, Ed., in (*7*)].
16. C. Brown and R. J. Seidler, *Appl. Microbiol.* **25**, 900 (1973).
17. D. M. McKnight, G. L. Feder, E. A. Stiles, *Environ. Sci. Technol.* **15**, 362 (1981).
18. R. C. Wissmar, unpublished data; J. Baross and C. Dahm, personal communication; R. C. Wissmar, paper presented at the Mount St. Helens "One Year Later" Symposium, Eastern Washington University, 17–18 May 1981.
19. J. Baross, C. Dahm, A. Ward, M. Lilley, J. Sedell, in preparation.
20. We thank S. Abella, A. Litt, and T. Edmundson for plankton identification; M. Perkins for help with the DOC analysis; L. Lehmiche for counting the bacteria; P. Poe, R. Donnelly, and T. Cline for the 4 April 1980 sampling; and Columbia Air Services for field laboratory facilities. Supported by NSF grant DEB 7811339 and U.S. Department of Agriculture Forest Service Agreement PNW-80-178. Contribution No. 565, College of Fisheries, University of Washington, Seattle.

20 April 1981; revised 24 August 1981

Venus: Chemical Weathering of Igneous Rocks and Buffering of Atmospheric Composition

Abstract. *Data from the Pioneer Venus radar mapper, combined with measurements of wind velocity and atmospheric composition, suggest that surface erosion on Venus varies with altitude. Calcium- and magnesium-rich weathering products are produced at high altitudes by gas-solid reactions with igneous minerals, then removed into the hotter lowlands by surface winds. These fine-grained weathering products may then rereact with the lower atmosphere and buffer the composition of the observed gases carbon dioxide, water vapor, sulfur dioxide, and hydrogen fluoride in some regions of the surface. This process is a plausible mechanism for the establishment in the lowlands of a calcium-rich mineral assemblage, which had previously been found necessary for the buffering of these species.*

The most important geochemical processes at work on the surface of the earth are erosion and transport of material by running water and the atmosphere. On Venus running water is absent, yet radar images of the surface suggest the existence of some active processes which modify landforms (*1*, *2*). Erosion produced by atmospheric motion has been suggested (*2*, *3*). We examine the role of the hot, reactive, lower atmosphere in surface modification.

Measurements by the Pioneer Venus entry probes and the Soviet Venera landers reveal the lower atmosphere of Venus to be roughly adiabatic (*4*), although some stratification is present (*5*).

The mean Venus surface temperature is 740 K, at a pressure of 92 bars. The observed lapse rate is about 8 K/km, compared with about 6.6 K/km on the earth (*4*, *5*). There is substantial disagreement between Soviet and American analyses of the composition of the lower atmosphere. A summary of the major and minor reactive constituents of the Venus atmosphere is given in Table 1. There are major uncertainties concerning the lower atmospheric abundance of water vapor (H_2O) and the sulfur-bearing gases COS, SO_2, and H_2S (*6*). Since reactions involving H_2O are crucial to weathering on Venus, we explored the consequences of a range (2×10^{-5} to 5×10^{-4}) of H_2O mole fractions. Chemical arguments based on the oxidation state of the crust and lower atmosphere (*7*) require the presence of COS; however, the Pioneer Venus mass spectrometer experiment was unable to detect the expected amount due to contamination by an ingested H_2SO_4 droplet. Because of the role sulfur plays in the chemistry of iron and in the buffering of the atmospheric oxidation state, more analyses of the lower atmosphere are required. Future experiments must be conducted with care to avoid contamination by cloud particles.

Table 1. Composition of the Venus atmosphere.

Species	Mole fraction	Source (*6*, *7*)
CO_2	0.97	Pioneer and Venera
CO	$\sim 2 \times 10^{-4}$	Earth-based
H_2O	2×10^{-5} to 5×10^{-4}	Pioneer and Venera
HCl	$>10^{-6}$	Earth-based
HF	$>10^{-8}$	Earth-based
N_2	~ 0.03	Pioneer and Venera
$SO_2 + S_2$	$<3 \times 10^{-4}$	Pioneer and Venera
H_2S	$\sim 10^{-6}$	Pioneer
COS	$>3 \times 10^{-6}$	Pioneer

Wind speeds in the lower atmosphere of Venus have been measured by the Venera landers and by radio tracking of the four Pioneer Venus entry probes (*8*). The Soviet results are consistent with surface winds of 0.5 to 1.5 m/sec, which agree with the Pioneer Venus near-surface data. The Pioneer Venus measurements also show free-atmosphere wind speeds of about 5 m/sec at an altitude of 12 km. This suggests that wind shear near the surface boundary layer will be greater at high altitude; still, the observed surface winds are probably adequate for moving fine-grained material (*9*).

Radar images and altimetry from ground-based radar and from the Pioneer Venus orbiting radar are too poor in resolution for detailed geomorphological interpretation. Earth-based radar images portray surface roughness on a scale of centimeters, Pioneer Venus measurements reveal roughness at a scale of 1 m, and global altimetry reveals surface features with a vertical resolution of 200 m and horizontal resolution of 100 km. In addition, the Pioneer Venus measurements allow estimates of the surface dielectric constant in surface cells 10 to 100 km across. Radar measurements show Maxwell Montes, a peak 10.8 km above the mean planetary radius, to be

0036-8075/82/0409-0181$01.00/0

the roughest portion of the planet on both the centimeter and meter scale. The Ishtar Terra plateau to the west of Maxwell has a lower surface dielectric constant, indicating a porous low-density surface covering (*10*). Aphrodite Terra, the only equatorial continental structure, is also rough on the meter scale. Aphrodite has not been observed in detail by earth-based radar. The highest altitudes found in this regions are about 6 km above the mean surface. These high land regions comprise less than 5 percent of the total surface of Venus. Features resembling craters have also been observed in ground-based images, and they appear to have been degraded (*11*).

We investigated gas-solid equilibria for a group of common igneous rock-forming minerals ranging from ultramafic forsterite to quartz. Since we do not know from direct observation what primary minerals are present on Venus, it is necessary to consider a wide range of possible assemblages. Venera 9 and Venera 10 reported concentrations of the radioactive elements Th, U, and K similar to those on terrestrial basalts, while Venera 8 reported a more granitic composition at its landing site (*12*). It is therefore necessary to investigate minerals representative of a range of terrestrial rock types. Thermodynamic data for the atmospheric components and the selected minerals are from Robie *et al.* (*13*).

A number of possible weathering reactions are given below; Fig. 1 shows the equilibrium boundaries for several of these reactions plotted on an integrated hypsometric curve of Venus elevations. The principal reactions considered are listed in Table 2. The reactions marked with asterisks are those that occur preferentially (proceed to the right) at higher altitudes. Reactions proceed in the opposite direction in lowlands; that is, tremolite breaks down.

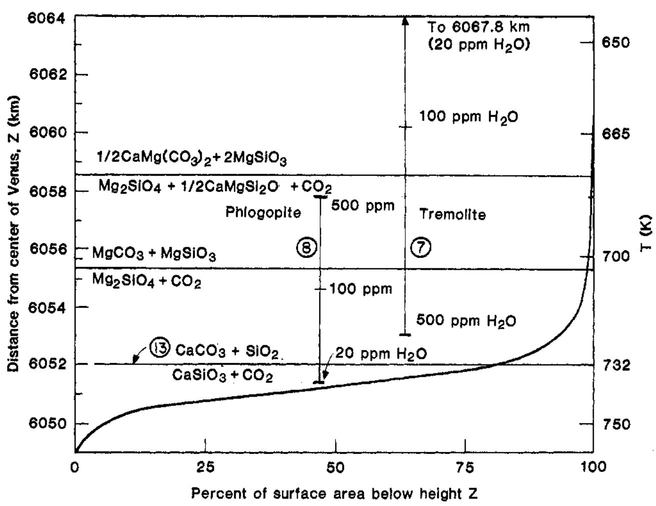

Fig. 1. Altitudes of equilibrium for selected weathering reactions on Venus. The Venus hypsometric curve is given as the curved solid line from lower left to upper right. Reactions 7 (diopside weathering to make tremolite) and 8 (fluorophlogopite formation) are sensitive to the H_2O mole fraction and are calculated for mole fraction values from 20 to 500 ppm.

Table 2. Possible weathering reactions on Venus.

$Mg_2SiO_4 + 2CO_2 \rightleftharpoons 2MgCO_3 + SiO_2$ forsterite magnesite quartz	(1)
$Mg_2SiO_4 + CO_2 \rightleftharpoons MgCO_3 + MgSiO_3$ enstatite	(2)*
$Fe_2SiO_4 + 4\ COS \rightleftharpoons 2FeS_2 + SiO_2 + 2CO + 2CO_2$ fayalite pyrite	(3)*
$MgSiO_3 + 2HF \rightleftharpoons H_2O + MgF_2 + SiO_2$ sellaite	(4)
$CaCO_3 + MgSiO_3 + CO_2 \rightleftharpoons CaMg(CO_3)_2 + SiO_2$ dolomite	(5)
$2CaAl_2Si_2O_8 + 5MgSiO_3 + SiO_2 + H_2O \rightleftharpoons Ca_2Mg_5Si_8O_{22}(OH)_2 + 2Al_2SiO_5$ tremolite	(6)*
$2CaMgSi_2O_6 + 3MgSiO_3 + SiO_2 + H_2O \rightleftharpoons Ca_2Mg_5Si_8O_{22}(OH)_2$ diopside	(7)*
$KAlSi_3O_8 + 3MgSiO_3 + 2HF \rightleftharpoons KMg_3AlSi_3O_{10}F_2 + 3SiO_2 + H_2O$ orthoclase fluorophlogopite	(8)*
$Mg_2SiO_4 + 2CO_2 + SO_2 \rightleftharpoons 2MgSO_4 + SiO_2 + 2CO$	(9)
$CaAl_2Si_2O_8 + SO_2 + CO_2 \rightleftharpoons CaSO_4 + Al_2SiO_5 + SiO_2 + CO$ anhydrite	(10)*
$CaMgSi_2O_6 + SO_2 + CO_2 \rightleftharpoons CaSO_4 + MgSiO_3 + SiO_2 + CO$	(11)*
$Mg_2SiO_4 + 1/2CaMgSi_2O_6 + CO_2 \rightleftharpoons 1/2CaMg(CO_3)_2 + 2MgSiO_3$	(12)*

It is interesting to note that diopside, olivine, and feldspar all show preferential weathering at high altitudes, assuming a mixing ratio close to 1×10^{-4} for H_2O in the lower atmosphere. Tremolite is unstable in the hottest lowlands of Venus, but would spontaneously form near the top of Maxwell as a weathering product of diopside or anorthite. The only places on the surface where this preferential weathering is expected are at the top of Maxwell or Aphrodite. Differential weathering may not only contribute to the rough disturbed surface observed by radar at high altitudes, but may also play a role in regulating the composition of the lower atmosphere of Venus.

Urey (*14*) originally suggested that the following reaction may apply to Venus:

$$\underset{\text{wollastonite}}{CaSiO_3} + CO_2\,(g) \rightleftharpoons \underset{\text{calcite}}{CaCO_3} + \underset{\text{quartz}}{SiO_2}$$

The equilibrium CO_2 pressure for this reaction at 740 K is 90 bars, remarkably close to mean Venus surface conditions. Since wollastonite is not a common mineral on the earth and is found only in metamorphosed rocks with an extremely high calcium content, the applicability of this reaction to Venus could be questioned. However, this buffer will be established if fine-grained calcium-rich weathering products (dolomite, calcite, anhydrite, and so on) are blown off the high mountains into the hotter lower regions of Venus. More likely HF, COS, SO_2, and H_2O are regionally buffered by thin (1 to 10 cm) layers of material removed from the highlands. This buffering is produced by reaction of the gases with metallic elements in the dirt: according to thermodynamic data, the minerals participating in the buffering of these gases are mainly calcium compounds, and a high $CaSiO_3$ activity is necessary (*7*). Lewis (*15*) pointed out that a water mole fraction as high as 10^{-3} in the atmosphere could be wholly removed by reaction with only a 15-m layer of dirt containing 10 percent CaO. With an H_2O mole fraction of 10^{-4} and a CaO content of 30 percent, this is reduced to 50 cm of dirt. Buffering could take place with a much thinner layer. The low dielectric constant observed on Terra Ishtar suggests that a large amount of low-density material is present in the highlands, to a depth of at least tens of centimeters. The observed wind speeds are probably sufficient to remove the weathering products into the lowland regions, but this is subject to experimental verification. Most sediment transport will occur during short, rare intervals of higher wind speeds. Large grains released by disaggregation of primary igneous rocks will be much harder to transport. Such large, relatively immobile grains would include quartz from granite weathering.

Of course, we cannot be sure which reactions, if any, actually occur and buffer the gas composition of the Venus lower atmosphere, but some type of chemical weathering can occur at any altitude. However, if Venus does have the surface igneous assemblages observed on the earth, the moon, and in meteorites, it is certain that chemical weathering will be more effective at higher altitudes, for any reasonable atmospheric H_2O mole fraction. Since Venus has very few mountains high enough for vigorous chemical weathering, such effects are probably confined to Maxwell and the top of Aphrodite. Future experiments will shed more light on the subject of chemical weathering on Venus by performing in situ chemical analyses with the same precision performed on Mars by the Viking landers. Specifically, the Ca/Si, Fe/Si, Mg/Si, and S/Si ratios in the soil and the atmospheric abundances of H_2O, HF, HCl, COS, SO_2, H_2S, and CO must be measured. Such analyses could be performed by x-ray fluorescence and gas chromatography–mass spectrometry on board a surface lander.

At present we are able to describe only one plausible geochemical transport process on Venus. Previous assumptions of gross chemical equilibrium between the lower atmosphere and surface of Venus are probably best justified by the existence of such a mechanism combined with the high surface temperatures and pressures. These assumptions lead us to the suggestion that the topography, radar properties, and lower atmosphere composition are interrelated.

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References and Notes

1. V. I. Moroz, *Cosmic Res.* **14**, 607 (1976).
2. C. P. Florenskii *et al.*, *Proc. Lunar Sci. Conf. 8* (1977), p. 2655.
3. C. Sagan, *J. Atmos. Sci.* **32**, 1079 (1975); *Nature (London)* **261**, 31 (1976).
4. A. Kliore and D. L. Cain, *J. Atmos. Sci.* **25**, 549 (1968); V. R. Eshleman, G. Fjeldbo, J. D. Anderson, A. Kliore, R. B. Dyce, *Science* **162**, 661 (1968); V. S. Avduevskii, M. Ya. Marov, M. K. Rozhdestvenskii, N. F. Borodin, V. V. Kerzhanovich, *J. Atmos. Sci.* **28**, 263 (1971); M. Ya. Marov, V. S. Avduevskii, M. K. Rozhdestvenskii, N. F. Borodin, V. V. Kerzhanovich, *Cosmic Res.* **9**, 521 (1971); M. Ya. Marov, V. S. Avduevskii, V. V. Kerzhanovich, M. K. Rozhdestvenskii, N. F. Borodin, D. L. Ryabov, *J. Atmos. Sci.* **30**, 1210 (1973).
5. G. Fjeldbo, A. J. Kliore, V. R. Eshleman, *Astron. J.* **76**, 123 (1971); A. Seiff, D. B. Kirk, R. E. Young, S. C. Sommer, R. C. Blanchard, J. T. Findlay, G. M. Kelly, *Science* **205**, 46 (1979).
6. J. H. Hoffman, V. I. Oyama, U. von Zahn, *J. Geophys. Res.* **85**, 7871 (1980).
7. J. S. Lewis, *Earth Planet. Sci. Lett.* **10**, 73 (1970); I. L. Khodakovskii, V. P. Volkov, Yu. I. Sidorov, M. V. Borosov, M. V. Lomonosov, *Icarus* **39**, 352 (1979); J. S. Lewis and F. A. Kreimendahl, *ibid.* **42**, 330 (1980).
8. V. S. Avduevskii *et al.*, *Cosmic Res.* **14**, 622 (1976); C. C. Counselman III, S. A. Gourevitch, R. W. King, G. B. Loriot, E. S. Ginsberg, *J. Geophys. Res.* **85**, 8026 (1980).
9. R. Greeley, *Proc. Lunar Planet. Sci. Conf. 12* (1981), p. 360.
10. G. H. Pettengill, S. Nozette, P. Ford, *Bull. Am. Astron. Soc.* **12**, 690 (1980).
11. R. M. Goldstein, R. R. Green, H. C. Rumsey, *J. Geophys. Res.* **81**, 4807 (1976).
12. M. V. Keldysh, *Icarus* **30**, 605 (1977).
13. R. A. Robie, B. S. Hemingway, J. R. Fisher, *U.S. Geol. Surv. Bull. 1452* (1978).
14. H. C. Urey, *The Planets* (Yale Univ. Press, New Haven, Conn., 1952).
15. J. S. Lewis, *J. Atmos. Sci.* **28**, 1084 (1971).
16. We thank the NASA Planetary Atmospheres program for support of this work.

6 August 1981; revised 15 January 1982

Locomotion in Moles (Insectivora, Proscalopidae) from the Middle Tertiary of North America

Abstract. *The locomotion of proscalopid moles, an extinct group restricted to North America, differed from that of other animals. Analysis of a newly discovered and relatively complete and articulated skeleton shows that the digging technique of proscalopids involved a combination of motions that has not been observed in modern fossorial insectivores. The many anatomical peculiarities of proscalopids are related to their specialized digging technique and justify their assignment to a new family of insectivores, the Proscalopidae.*

Proscalopids, a group of moles known only from the Oligocene and Miocene of North America, had a specialized skeletal morphology that was different from any Recent mammal. The scarcity of fossil remains, however, has limited the inferences that could be made about the evolutionary history and the function of the specializations of these mammals. Only isolated teeth, bones of the forelimb, and some cranial elements had been reported (*1*, *2*), and only recently was it shown that the bones belonged to the same type of animal (*3*, *4*). The breadth and unusual shape of the humerus led early investigators to suggest that it was adapted for digging, and proscalopids have been classified in the same family as the fossorial golden moles (Chrysochloridae) (*5*, *6*), palaeanodont edentates (Epoicotheriidae) (*7*), and true moles (Talpidae). Although some investigators suggested that proscalopids represented a distinct family of insectivores (*1*, *8*), most have regarded them as talpids (*1*, *3*, *4*).

A nearly complete and partially articulated skull and skeleton of a proscalopid (genus *Mesoscalops*) was found in the siltstones of the Miocene Deep River Formation (probably of Hemingfordian age) of western Montana (*9*). Analysis of this skeleton has revealed that proscalopids differ more from other small mammals than has been recognized, in both gross anatomy and mode of locomotion. The digging stroke in proscalopids may resemble that of modern chrysochlorids more than that of talpids (*1*). The many differences preclude a family-level relation between proscalopids and talpids.

Anatomically, the proscalopids are a peculiar blend of specializations, some of which are found in golden moles and fewer in true moles. For example, the short skull of proscalopids is most similar to that of chrysochlorids (*8*) in the prominent shelves that extend toward the side from the snout, the deep basicranium, and the prominent nuchal crest. The nuchal crest often extends onto the top of the posterior portion of the zygomatic arch, which is continuous with a broadened flange that covers the squamosal region. Talpids lack all of these features but resemble proscalopids in dental characteristics, particularly in the W-shaped ectoloph of the molars. The robust cervical vertebrae of proscalopids have unusually large neural spines, and vertebrae two through five are fused. The neural spines on thoracic vertebrae two to five (Fig. 1A) are much higher than those in either golden or true moles. A prominent fossa (*f* in Fig. 1A) covers the anterior surface of the spines in the proscalopid.

Because many of these features are found in modern animals that use the head in digging, such as chrysochlorids

0036-8075/82/0409-0183$01.00/0