Lunar Ring Dikes from Lunar Orbiter I

Abstract. *Orbiter photographs of the wall of a large circular formation on the moon show that the wall is a convex body resembling a flow of viscous lava. The slopes are less than the angle of repose of dry rock; hence an explanation in terms of mass wastage is hard to support. The viscosity is approximately 10^{13} centimeter-gram-second units, indicating an acid lava.*

Although it is widely believed that most lunar craters are the result of impact, it has also been repeatedly suggested (*1*) that some of the large lunar craters may correspond to the surface expression of what, on earth, are called ring dikes. A dike is a fissure in bedrock filled with congealed magma; despite the name, it is not a wall. A ring dike is one which forms a more or less complete ring, from 2 to 20 km or more in diameter, with a breadth at any point ranging from 1 m to several kilometers. The magma of a ring dike is usually of acidic (over 66 percent SiO_2) or intermediate (52 to 66 percent SiO_2) composition. Ring dikes are usually observed on eroded surfaces; when the magma was emplaced, the ring dike may have extended to the surface and acted as the feeder for a ring of volcanics like those of the Valles caldera (*2*). It is these surface volcanics which are compared to the lunar craters.

Lunar Orbiter I has provided 32 photographs of Apollo landing site A 9.2, in Oceanus Procellarum, near 2°S latitude and 43°W longitude. Figure 1 shows part of the structure, sometimes called the Flamsteed Ring (diameter about 100 km), which surrounds the landing site of Surveyor I. This crater wall is light in color and has sharp convex scarps which bound the wall on both sides (though the lighting makes the scarp difficult to see on the northeast side). Close examination of large-scale prints shows at least nine craters along the boundary of the hilly region, which have been partially invaded by the wall material. This suggests that the wall material is younger than the mare material.

We interpret these topographic features as the result of the extrusion of lavas of intermediate or acidic composition. These lavas, being much more viscous than basic lavas (SiO_2 less than 52 percent), typically form steep-sided, occasionally blocky flows of very limited range (Fig. 2) without summit craters. Cotton (*3*) presents good examples of these flows, which he refers to as "convex lava flows" or coulées, as well as of cumulo-domes, that is, dome-like elevations formed by the extrusion of viscous lavas. Most of the elevations of the Flamsteed Ring appear similar to the coulées and cumulo-domes of Cotton in being light-colored convex features without summit craters. The similarity extends to the limit of resolution of the Lunar Orbiter photographs, which, under grazing incidence sunlight, show that the Flamsteed Ring and comparable features elsewhere have a rough blocky surface with, in some places, concentric rings.

It is probably not possible to interpret the Flamsteed Ring as the result of basaltic flows, despite the lower value of gravity on the moon. The argument is as follows: (i) Each hill appears to consist of a single flow, since no scarps are seen except the well-marked scarp at the base.

Moreover, the pattern of flow markings varies continuously from the base to the top of the hill. (ii) For a single flow, the equation of Jeffreys (*4*) may be applied, with adaptation of an approach used by Nichols (*5*):

$$V = (g \sin A \, d^2 \rho)/3\mu \qquad (1)$$

where V is the velocity of the flow, A the slope angle, d the depth, ρ the specific gravity, and μ the viscosity. In the work of Nichols and Jeffreys, the slope was that on which the viscous liquid was flowing; here we use the slope of the hill itself, which certainly tends to cause the outer parts of the mass to move over the inner parts. We therefore take d as one-half the true thickness, 300 m, from the Surveyor pictures which show the ridge (*6*). Lunar gravity is about 160 cm/sec^2; A is at most 16° on the Surveyor pictures; for ρ we take 3 g/cm^3. Then

$$V = 10^{10}/\mu \qquad (2)$$

in centimeters per second.

If we substitute a typical basaltic viscosity of 10^2 to 10^5 cgs units (*7*) then, even for the upper limit, the steady flow comes out at about 1 km/sec, that is, the ridge would immediately collapse. Hence it probably does not represent a basaltic flow. In fact, convex basalt shields are usually the result of multiple flows, and hence show multiple scarps.

To obtain a reasonable value for the viscosity of the mass regarded as a single flow, we assume that the flow

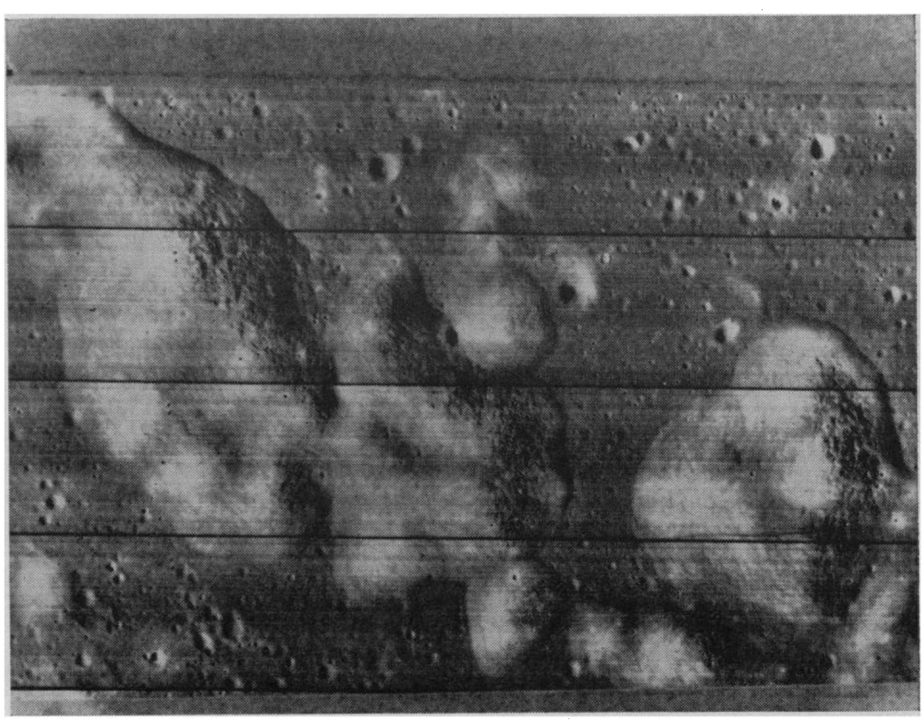

Fig. 1. Portions of the Flamsteed Ring near the Surveyor I site. The horizontal strips are each about 1.6 km in width.

Fig. 2. Rock Mesa. A frothy dacitic flow in Lane-Deschutes County, Oregon. [Courtesy of Oregon Department of Geology and Mineral Industries]

occurs so slowly that it is at last arrested by cooling and congealing. The depth of congealing would have to be at least 10 m on a huge mass such as this to arrest the flow. The time required for cooling to reach a depth of a meters is of the order of magnitude

$$t \approx D/a^2 \qquad (3)$$

where t is the time, and D the coefficient of thermal diffusion. Here $D = k/\rho c$, where k is the thermal conductivity, and c the heat capacity. For granite, D is roughly 0.009 cm^2/sec whence t is approximately 10^8 sec for a depth of 10 m. Since one side of the hill measures about 1 km, the approximate value of the velocity of flow V is about 10^{-3} cm/sec, and hence the viscosity is 10^{13} cgs units. This value indicates a highly acidic magma (*8*).

The alternative possibility is mass wastage, that is, the motion of masses of rock or soil. The possible modes of mass wastage are listed in texts on geology. For points near the equator of the moon, all processes involving water or ice may be eliminated. The mean temperature, which is approximately the same as the temperature at a depth of a few meters, is about 240°K. At this temperature, the vapor pressure of ice is about 0.3 mm-Hg (from handbook tables). The corresponding loss of mass by sublimation into a vacuum is about 1 g/cm^2 per minute. At this rate, the loss from an area 100 m in diameter would in 1 day equal the whole lunar atmosphere. It is thus extremely doubtful if any such areas exist. It is hard to see how ice could be sealed off, so that escape of vapor could not occur, and at the same time be involved with moving masses of rock.

According to Wahrhaftig and Cox (*9*) a study of 200 Alaskan glaciers shows that the objects called rock glaciers are not, in fact, merely glaciers of dry rock, but have ice a few feet below the surface; hence this method of rock wastage would not be expected on the moon.

Processes of rock wastage which do not necessarily involve water or ice and hence must still be considered are: (i) talus formation, (ii) rock creep, and (iii) landslides.

Of these, talus formation is the principal. Talus is the mass of broken rock which collects at the foot of a steep natural slope. Talus slopes are at or near the angle of repose of the material, namely 30° to 40° on the earth. Lunar slopes are expected to show slightly greater angles of repose (*10*). By contrast, maximum slopes on the Flamsteed Ring are about 16°, as measured on the Surveyor photographs. They are less than 26°, judging from the absence of shadows and the known height of the sun; as judged from a comparison of heights and widths they are about 18°. Thus they do not reach the values required for talus slopes.

Again, terrestrial talus slopes are nearly always concave (*11*). One reason for this is (*12*) that the upper parts of the slope represent compacted material not yet detached, while the lower parts represent loose material which has just rolled down. The observed slopes of the Flamsteed Ring, on the other hand, are nearly always convex, especially in the steeper parts.

Again, on talus slopes, there is a strong tendency for the larger boulders to roll out to the edge of the slope (*11, 13*). No large boulders are observed at the foot of the slopes of the Flamsteed Ring, although some are seen higher up. We conclude that talus slopes are absent from the Flamsteed Ring.

One would then not expect the minor manifestations of rock wastage, namely rock creep and landslides, since these usually accompany the formation of talus slopes. If there is not enough rock weathering to produce talus slopes, these phenomena are not likely to be seen. In addition, landslides require slopes near the angle of repose, which are missing. Rock creep would be expected to produce concave slopes if there were any range in the rate of movement of different particles. We conclude that the observed slopes are not due to rock wastage.

Hence the above explanation in terms of acid lavas is probably the correct one; and since the Flamsteed Ring is roughly circular, the observations support the idea that it is the surface manifestation of a ring dike. In view of the siliceous extrusions described here, and in view of the fact that the ring dike phenomenon is normally accompanied by extensive ash flows we here suggest that the finely divided material in the Surveyor pictures represents the surface of a lunar ash flow tuff, of acid or intermediate composition.

The recent Russian gamma-ray data on the abundance of U, Th, and K at the moon's surface (*14*) have been interpreted as indicating that very acid rocks such as granites do not make up the lunar surface. They have further equated tektites with granite. In fact, however, tektites fall below not only their classification of "granites," but also their classification of "intermediate" rocks in respect to the radioactive elements. By plotting their predictions for intermediate rocks against the observations, it can be shown that intermediate rocks are not excluded by their observations. In addition, as the authors themselves have emphasized, the necessity of allowing for background corrections, which are very uncertain and which account for 90 percent of the measured values, makes it somewhat difficult to draw firm conclusions from this pioneering effort.

JOHN A. O'KEEFE
PAUL D. LOWMAN, JR.
WINIFRED S. CAMERON
Goddard Space Flight Center, Greenbelt, Maryland

References and Notes

1. H. Jeffreys, *The Earth* (Cambridge Univ. Press, Cambridge, ed. 3, 1952), p. 352; J. Green, *Proc. Lunar and Planetary Exploration Colloquium* (North American Aviation, Downey, Calif.), 1, 1 (1959); Douglas Paper 4038 (Douglas Advanced Research Laboratory, Huntingdon Beach, Calif., 1966); G. Fielder, *Lunar Geology* (Lutterworth, London, 1965), chap. 9; G. J. H. McCall, *Ann. N.Y. Acad. Sci.* **123**, 843 (1965); W. E. Elston, *ibid.* p. 817.
2. R. L. Smith, *U.S. Geol. Surv. Prof. Papers* **424D**, 145 (1961).
3. C. A. Cotton, *Volcanoes as Landscape Forms* (Whitcombe and Tombs, Christchurch, N.Z., 1952), chap. 11.
4. H. Jeffreys, *Phil. Mag. Ser. 6* **49**, 793 (1925).
5. R. H. Nichols, *J. Geol.* **47**, 290 (1939).
6. E. A. Whitaker, *Science* **153**, 1550 (1966).
7. C. K. Wentworth, M. H. Carson, R. H. Finch, *J. Geol.* **53**, 94 (1945).
8. E. E. Wahlstrom, *Introduction to Theoretical Igneous Petrology* (Wiley, New York, 1950).
9. C. Wahrhaftig and A. Cox, *Bull. Geol. Soc. Amer.* **70**, 383 (1959).
10. R. Baldwin, *The Measure of the Moon* (Univ. of Chicago Press, Chicago, 1963), p. 248.
11. A. K. Lobeck, *Geomorphology* (McGraw-Hill, New York, 1939), p. 81.
12. A. E. Scheidegger, *Theoretical Geomorphology* (Prentice-Hall, Englewood Cliffs, N.J., 1961), p. 72.
13. O. D. von Engeln, *Geomorphology* (Macmillan, New York, 1942), p. 245.
14. A. P. Vinogradov, Iu. A. Surkov, G. M. Chernov, S. S. Krinozov, *Geokhimiya* **8**, 891 (1966).
15. We thank the Lunar Orbiter Project Office at Langley Research Center, Hampton, Va., and Dr. M. J. Swetnick for the pictures.

22 November 1966

Pressure-Induced Phase of Sulfur-Selenium

Abstract. *Crystals of a fibrous phase of sulfur-selenium obtained at 20 kilobars and 280°C are trigonal, the most probable space groups being* $P3_1$ *and* $P3_2$, *with* $a = 7.85$, $c = 4.62 \pm 0.01$ *Å. The unit cell contains nine atoms, and the measured density of 3.20* g/cm^3 *implies five sulfur and four Se atoms. The structure contains mixed atom helices of 1.54 Å pitch and 0.91 Å average radius.*

In a continuing investigation of group VI A elements a new pressure-induced sulfur-selenium phase has been found. The phase is fibrous but is not isostructural with the fibrous sulfur phase (II) (*1*). In fact, we have also found that some selenium does dissolve in the fibrous sulfur phase.

Starting materials were pure (99.999+ percent) Se and S (American Smelting and Refining Company). A one-to-one mixture (atom percent) was put into a fused silica tube, evacuated, and sealed. The mixture was melted and kept at 250°C for 2 hours and annealed at 80°C for 110 hours. It was then removed from the tube and ground and mixed thoroughly in an attempt to insure homogenization. Some of this material was then packed into tantalum containers and subjected to pressure and heating in furnaces and piston cylinder devices similar to those described by others (*1*, ref. 1). The fibrous S-Se phase reported here was prepared in a furnace (2.54 cm diameter) at 20 kb. The temperature was raised to 550°C and held there for 10 minutes; the temperature was then reduced to 280°C and maintained there for 56 hours. The resulting material was not homogeneous but that part of the sample in the bottom portion of the sample capsule was red-brown, crystalline, and fibrous. A measurement of the density of isolated crystals of the fibrous form by the flotation technique gave 3.20 g/cm^3.

An apparently single crystal of the fibrous sulfur-selenium was aligned along the fiber axis with oscillation photography; CuK_α radiation was used, and Weissenberg photographs were taken. Lattice constants were determined from Buerger precession camera photographs (MoK_α radiation). The diffraction symmetry of all the photographs is $6/m$, the only systematic absences being those reflections ($00l$) for which l is not equal to $6n$. The lattice constants of the particular crystal photographed are: $a = 7.85$, and $c = 4.62 \pm 0.01$ Å. Hexagonal selenium has $a = 4.355$, $c = 4.949$ Å. The sublattice obtained by a 30° rotation from the unit cell of the sulfur-selenium phase has lattice constants $a = 4.53$ Å and $c = 4.62$ Å. It appears then that the sulfur-selenium unit cell must contain nine atoms. A cell content of five S and four Se atoms gives an x-ray density of 3.20 g/cm^3 equal to the measured density.

Any space group giving diffraction symmetry $6/m$ satisfying the conditions for these helices must contain screw axes. Further, because of the length of the c-axis, the helices in the sulfur-selenium phase must have three atoms per turn as in hexagonal selenium itself. No hexagonal space group giving diffraction symmetry $6/m$ can satisfy the requirements for this structure. Thus it appears that the $6/m$ is only an apparent diffraction symmetry; the more probable diffraction symmetry is $\bar{3}$. When crystals with this symmetry are 120° rotation-twinned, they give the apparent symmetry observed. This is analogous to the case of selenium itself (*2*) in which the twinning of crystals with diffraction symmetry $\bar{3}m$ leads to apparent symmetry $6/mmm$.

Thus the most probable space groups to which the fibrous $S_{0.555}Se_{0.444}$ belongs are $P3_1$ or $P3_2$. It is possible also that the two enantiomorphs are cocrystallizing in the twinned crystals.

Thus far the preliminary refinement of the x and y parameters with the use of the Busing-Martin-Levy (*3*) program (modified for use on the IBM 360 computer) and only the $hk0$ intensity data (for which there is no overlapping of nonequivalent reflections) indicates that the helix radius is close to 0.91 Å; the pitch, given by $c/3$ is 1.54 Å. This implies an average S-Se distance (*4*) of 2.20 Å as compared with a calculated one of 2.18 Å based on a value of 2.34 Å for an Se-Se distance and 2.05 Å for an S-S distance.

For Se, the pitch and radius of the helix are 1.65 and 0.95 Å, respectively (*4*). Thus the larger a-axis of the subcell (see above) implies poorer packing efficiency of the sulfur-selenium phase than of the hexagonal Se phase.

Spacings were calculated with the lattice constants determined from the Buerger precession camera photographs. It is seen in Table 1 that the calculated spacings compare well with those measured on an x-ray powder photograph of the material. All nonequivalent sets of indices are given.

There appears to be a range of solid solutions having the same fibrous structure, but the limits have not yet been determined. The new phase is not nearly as stable as the fibrous sulfur phase, in which case a specimen 15 months