Our results have a bearing on the reversal of eutrophication in lakes where N_2 fixation is a major supplier of algal N (*17*). We have shown that N_2 fixation is inhibited by freshly added Cu at concentrations as low as 1/200 of those normally used to kill blue-green algal blooms. We have also shown that low levels of Cu favor the more desirable algal groups such as diatoms, at least in laboratory incubations of lake water.

In the lake a predominance of algae other than blue-greens in early spring is unlikely because *Aphanizomenon* normally dominates both early and late spring blooms when algal growth is mainly on NO_3-N and N_2-N, respectively. The dominance of *Aphanizomenon* is due, apart from the N_2 fixation in late spring, to its ability to regulate its buoyancy and remain at a depth with favorable light and nutrients (*18*). This buoyancy also enables *Aphanizomenon* to dominate the muddy-water winter phytoplankton and provide a large "inoculum" for the spring bloom. Suppression of N_2 fixation will most probably alter the current ecological balance away from *Aphanizomenon* only between late spring, when the winter store of NO_3-N has been used up, and autumn. At present in late summer there are sometimes moderate phytoplankton crops dominated by N-limited algae other than blue-greens.

In Clear Lake, where an estimated 500 tons of N_2 is fixed annually by blue-green algae, the low Cu additions we propose could be used to reduce the total N budget of the lake by 40 to 50 percent. This could be accomplished at a fraction of the cost required to remove inflowing sewage N by advanced wastewater treatment. Both wastewater treatment and trace Cu addition are techniques which need to be used in the foreseeable future. Neither system provides a "once only" lake cleanser. A suitable tertiary sewage treatment would include a denitrification stage, with an added carbon energy source. Since sewage N represents only 10 percent of the annual N budget of the lake (*8*), suppression of N_2 fixation by trace levels of Cu is a cheaper and more effective way of reversing eutrophication in this lake. However, a successful method of controlling N_2 fixation, with no tertiary sewage treatment or change in river inflow, would decrease the absolute amount of N entering the lake, but increase the percentage contribution of sewage N and thus its importance. Both advanced wastewater treatment and some method of directly inhibiting N_2 fixation by blue-green algae would be needed to end the yearly occurrence of serious nuisance blooms.

ALEXANDER J. HORNE
Division of Sanitary Engineering, University of California, Berkeley 94720

CHARLES R. GOLDMAN
Division of Environmental Studies, University of California, Davis 95616

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Detection of Radon Emission at the Edges of Lunar Maria with the Apollo Alpha-Particle Spectrometer

Abstract. *The distribution of radioactive polonium-210, a decay product of radon-222, shows enhanced concentrations at the edges of lunar maria. Enhancements are seen at the edges of Mare Fecunditatis, Mare Crisium, Mare Smythii, Mare Tranquillitatis, Mare Nubium, Mare Cognitum, and Oceanus Procellarum. The observation is indicative of the transient emission of radon gas from the perimeters of lunar maria.*

The noble gas ^{222}Rn is produced in the natural decay chain of uranium. It decays with a half-life of 3.8 days by the emission of an alpha particle. Under certain conditions ^{222}Rn may diffuse through the lunar regolith and appear above the lunar surface before undergoing radioactive decay. Moreover, ^{222}Rn has a descendant, ^{210}Po, which is also an alpha-particle emitter but delayed by the 21-year half-life of ^{210}Pb. The orbiting alpha-particle detectors aboard the Apollo 15 and Apollo 16 spacecraft had spatial and energy resolution sufficient to identify and locate concentrations of either species.

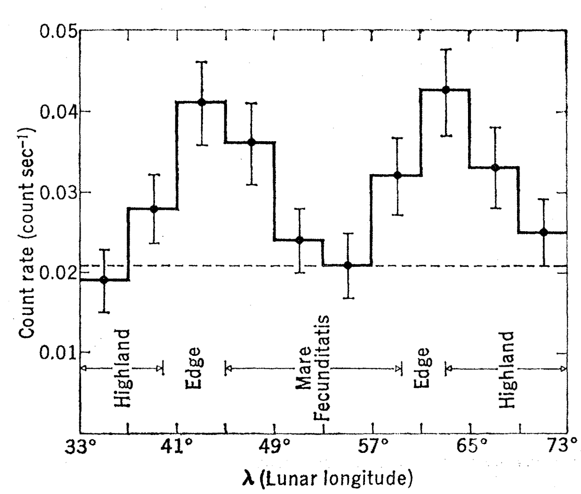

Fig. 1. Count rate of ^{210}Po across Mare Fecunditatis. The dashed line at 0.021 count sec^{-1} shows the background level.

Table 1. The ^{210}Po decay rate at maria edges. Rates are $\times 10^{-3}$ count sec^{-1} = 0.36×10^{-3} disintegration sec^{-1} cm^{-2} at the lunar surface (with a background of 21×10^{-3} count sec^{-1} subtracted). "In" and "Out" refer to the mare surface and the surrounding highlands, respectively.

Mare	In: 200–350 km	In: 75–200 km	Edge ± 75 km	Out: 75–200 km	Out: 200–350 km
			Apollo 15		
Fecunditatis	-0.1 ± 4.3	11.1 ± 4.4	12.5 ± 3.5	8.1 ± 5.8	No data
Crisium	No data	No data	20.1 ± 5.2	4.1 ± 5.6	-5.6 ± 8.0
Smythii	No data	-5.6 ± 10.1	14.1 ± 4.2	9.0 ± 6.3	6.2 ± 7.5
Procellarum	-7.7 ± 5.3	1.5 ± 3.8	5.4 ± 4.1	4.0 ± 4.2	-6.7 ± 6.2
Imbrium	3.4 ± 4.5	2.3 ± 4.2	4.6 ± 3.1	No data	No data
Tranquillitatis	2.1 ± 6.3	-7.7 ± 2.8	8.0 ± 2.6	No data	No data
Serenitatis	No data	5.1 ± 4.4	4.0 ± 2.9	4.5 ± 3.4	No data
Total Apollo 15	-0.1 ± 2.5	1.0 ± 1.6	8.4 ± 1.3	5.3 ± 2.1	-1.9 ± 4.1
			Apollo 16		
Fecunditatis	No data	6.8 ± 2.1	19.5 ± 3.1	7.1 ± 2.8	8.3 ± 7.1
Smythii	No data	3.4 ± 4.7	9.5 ± 3.1	10.9 ± 3.0	7.5 ± 5.3
Tranquillitatis	No data	No data	11.6 ± 3.8	4.7 ± 2.4	9.3 ± 2.7
Nubium	No data	No data	11.5 ± 3.6	8.1 ± 2.8	3.9 ± 3.4
Cognitum	No data	6.6 ± 2.8	11.2 ± 2.7	7.3 ± 3.7	No data
Total Apollo 16		6.5 ± 1.7	13.3 ± 1.5	7.7 ± 1.3	7.6 ± 1.9
Total Apollo 15 and Apollo 16	-0.1 ± 2.5	2.9 ± 1.3	9.8 ± 1.0	6.7 ± 1.2	4.9 ± 1.8

In earlier reports we have noted ^{222}Rn emanation from the crater Aristarchus (*1*) and a spatially varying surface distribution of ^{210}Po (*2*). In further refining our observation of the spatial variations of ^{210}Po and attempting to associate these variations with lunar features, we noted a remarkable correlation between ^{210}Po activity and the edges of lunar maria. Figure 1 demonstrates this effect as the field of view traverses Mare Fecunditatis. The data are summed over about 5° of latitude, and each bin contains the data from 4° of longitude (150 by 120 km). The important feature of these data is that the ^{210}Po concentration varies rapidly over distances corresponding to only a few degrees on the lunar surface. In addition, the maximum intensity observed coincides with the edges of the mare whereas the activity to either side of the mare and across the center is consistent with the background. The peak rate is 0.044 count sec^{-1} corresponding to 1.6×10^{-2} disintegration sec^{-1} cm^{-2} at the surface.

Figure 2 shows the observed energy spectra, demonstrating that this effect is due to ^{210}Po decays. Figure 2A shows energy spectra taken over the edges of Mare Fecunditatis (solid line) and over the central part of the mare (dashed line). The two spectra have been normalized to equal observation times. Figure 2B shows the difference between the two spectra, clearly indicating the presence of excess ^{210}Po at the edges of the mare. There is also present a signal from differences in ^{222}Rn but at much lower concentrations. If ^{222}Rn were in radioactive equilibrium with its descendant ^{210}Po, its activity would exceed that of ^{210}Po by at least a factor of 2. Thus the radon emission that causes the ^{210}Po excess at the edges of Mare Fecunditatis is time dependent and an example of the type of transient lunar radon emission reported earlier (*2*).

Mare Fecunditatis shows this effect most dramatically of all the lunar maria we observed. In an effort to determine if the edge effect is unique to this mare or if it is a more general feature of lunar maria, we examined all the data from the Apollo 15 and Apollo 16 missions. Table 1 shows the count rate of ^{210}Po as a function of distance from a mare edge for all the available data. Mare Undarum and Mare Spumans were not considered because of the difficulty of accurately determining the edge position. For all of the maria observed on the Apollo 15 and Apollo 16 missions, with the sole exception of the Apollo 15 observation of Mare Serenitatis, there is an increase in the ^{210}Po count rate at their edges. The combined

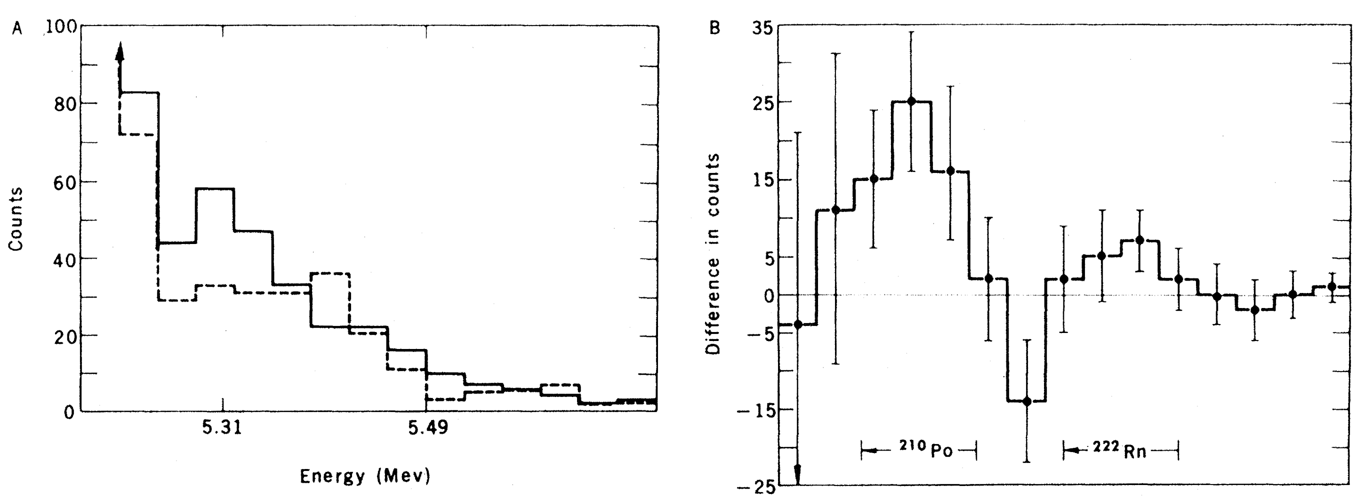

Fig. 2. (A) Energy spectra at Mare Fecunditatis: (solid line) spectrum at the edges of the mare ($\lambda = 40°$ to 45°E and 60° to 65°E); (dashed line) spectrum over the center of the mare ($\lambda = 47°$ to 57°E). A calibration source, not shown, has an energy of 5.1 Mev. (B) Difference between the two regions, showing excess ^{210}Po and ^{222}Rn at the edges of Mare Fecunditatis.

data from all observations clearly show that the effect is universal. The data from the two missions need not agree because the ground tracks did not overlap in detail at the mare edge crossings and because there may have been additional radon emanation during the 9 months between observations.

There are two results which any model for the origin of the edge effect must explain:

1) The distribution of ^{210}Po activity is sharply peaked at the edges of the maria.

2) The ^{210}Po activity exceeds that of its progenitor ^{222}Rn at the edges of the maria, implying that the process which leads to the emission of ^{222}Rn is varying in time. The time scale of the variation is less than a few times the effective half-life of ^{210}Po (21 years).

In any hypothesis based on an external process, which frees radon from lunar material, for example, meteorite bombardment or mass slumping, it would be necessary to explain why the process is so pronounced at the edges of the maria. Also, an external process would involve an amount of lunar material that is too large. For example, if one assumes that all the existing radon is released instantaneously from all the lunar material disturbed by a meteorite impact, then the total mass of lunar material required is several tenths of a gram per square centimeter per year. In view of the persistence of lunar surface features on a time scale of 10^9 years, the large mass requirement appears to rule out external processes as a source of radon.

Let us hypothesize that radon is a very minor component of the gases released at the lunar surface. The peak activity rate of ^{210}Po at the edge of Mare Fecunditatis is 1.6×10^{-2} disintegration sec^{-1} cm^{-2}. If we assume radioactive equilibrium for the purpose of this estimate, the implied peak diffusion rate of ^{222}Rn is approximately twice the decay rate of ^{210}Po. Averaged over the lunar surface, the diffusion rate would be of the order of 10^{-2} atom sec^{-1} cm^{-2}. Measurements of other gases in the lunar atmosphere indicate that the total concentration of the sum of O_2, CO_2, N_2, CO, and H_2O, which are mostly of solar origin, is less than a few times 10^4 molecule cm^{-3} on the nighttime side (*3*). We assume that these gases have a scale height of 10^7 cm and a loss time in the lunar atmosphere of 10^7 seconds (*4*). Therefore, if radon atoms constituted only one part in 10^5, on the average, of gases emitted from the surface, present measurements of the density of the lunar atmosphere would not be exceeded. Middlehurst (*5*) and Cameron (*6*) have studied historical records of transient optical events on the lunar surface. The phenomena have been recorded over several centuries of observation and include sudden brightenings, color changes, and obscurations. Middlehurst has noted that the sites of these events tend to group at the mare edges and near prominent young craters. The general correlation of both transient optical events and time-varying radon emanation with the edges of the maria is particularly significant in light of the fact that the crater Aristarchus, from which we detected ^{222}Rn emission during the Apollo 15 mission (*1*), is the most frequently reported site of transient events. Salisbury *et al.* have mapped the spatial distribution of dark-haloed craters on the visible lunar surface (*7*) and have found that they tend to occur at the edges of the maria. These craters are generally small, are surrounded by material of low albedo, and may be of volcanic origin (*8*). A factor that could be common to the polonium effect, the transient optical events, and the occurrence of dark-haloed lunar craters is transient venting of volatile materials at the edges of the maria. The polonium enhancement could be due either to variable diffuse venting over a large portion of the mare perimeters or to a few well-localized centers. Perhaps optical events are detectable when the gas venting is most pronounced and localized. If it is true that dark-haloed craters are of volcanic origin, then in the past the edges of the maria were areas at which gas venting occurred. The results presented here establish that at least one gas, radon, is being emitted from the edges of the maria at the present time.

PAUL GORENSTEIN*
LEON GOLUB
PAUL BJORKHOLM
American Science and Engineering, Cambridge, Massachusetts 02139

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* Present address: Center for Astrophysics, Smithsonian Astrophysical Observatory–Harvard College Observatory, Cambridge, Massachusetts 02138.

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Radon-222 from the Island of Hawaii: Deep Soils Are More Important than Lava Fields or Volcanoes

Abstract. *The mean flux of radon-222 atoms from the island of Hawaii is 0.45 atom per square centimeter per second. Lava fields occupy 50 percent of the land area, but their radon flux is only 1 percent of that from deep volcanic soils. The island yields approximately 10 curies of radon-222 per hour to the air surrounding it. The radon-222 contribution of volcanoes is negligible.*

The island of Hawaii, situated 3800 km or more from the nearest upwind landmass, is ideally located for the use of naturally occurring ^{222}Rn (half-life $T_{1/2} = 3.82$ days) and its long-lived daughter ^{210}Pb ($T_{1/2} = 22$ years) in both local and large-scale circulation studies (*1*). The purpose of the work reported here was to determine the ^{222}Rn exhalation from the lava and soils in order to provide a better understanding of the distribution of ^{222}Rn and its daughter nuclides in the air over the island.

On the basis of earlier studies of radon exhalation (*2*), it can be expected that the land surface of Hawaii will contribute ^{222}Rn to the island atmosphere at an average rate dependent upon three factors: (i) the concentration of ^{226}Ra in the rocks and soils of the island; (ii) the fraction of the total number of ^{226}Ra atoms that are located on or near the surface of mineral grains and soil particles in a position that favors the escape of the newly formed daughter atoms into the soil gas; and (iii) the physical character-