per year for total seismic energy release within the earth. The uncertainty is due primarily to the difficulty of estimating the ranges of natural events. However, the average rate of seismic energy release within the moon is far below that of the earth. Thus, internal convection currents leading to significant lunar tectonism are probably absent. Further, the absence of conspicuous offset surface features and of compressional features such as folded mountains is evidence against significant lunar tectonic activity, past or present. The outer shell of the moon appears to be cold, rigid, and tectonically stable compared to the earth, except for the minor disruptive influence correlated with lunar tides.

Since this report was written, a third seismic station has been installed near Hadley Rille as part of the Apollo 15 mission. Two moonquakes from the most active source (A_1 zone) were recorded by the three stations of the Apollo seismic network during the first two perigee periods following activation of the new station. The epicenter has been tentatively located at 21°S, 28°W, 600 km SSW of stations 12 and 14. The depth of the focus is about 800 km—deeper than any known earthquake. Unlike the earth, the moon must be sufficiently rigid at this depth to sustain appreciable shear stress. The remaining foci have not yet been located.

In addition to the repeating moonquakes, moonquake "swarms" have been discovered. During periods of swarm activity, events occur as frequently as one event every 2 hours over intervals lasting several days. The source of these swarms is unknown at present. The occurrence of swarms does not appear to be related to lunar tides, although present data are not sufficient to rule out this possibility.

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References and Notes

1. G. Latham, M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksoz, R. Wiggins, J. Derr, F. Duennebier, *Apollo 11 Preliminary Science Report* (NASA SP-214, 1969), p. 143; *Science* **167**, 455 (1970); "Proceedings of the Apollo 11 lunar science conference," *Geochim. Cosmochim. Acta* (Suppl. 1) **3**, 2309 (1970); M. Ewing, G. Latham, F. Press, G. Sutton, J. Dorman, Y. Nakamura, R. Meissner, F. Duennebier, *Highlights of Astronomy* (Reidel, Dordrecht, Netherlands, 1970).
2. G. Latham, M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksoz, R. Wiggins, R. Kovach, *Apollo 12 Preliminary Mission Science Report* (NASA SP-235, 1970), section 3, p. 39.
3. G. Latham, M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksoz, R. Meissner, F. Duennebier, R. Kovach, M. Yates, *Science* **170**, 620 (1970).
4. G. Latham, M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksoz, F. Duennebier, D. Lammlein, *Apollo 14 Preliminary Science Report* (NASA SP-272, 1971), p. 133.
5. G. Latham, M. Ewing, F. Press, C. Sutton, *Science* **165**, 241 (1969).
6. E. Opik, *Astron. J.* **66**, 60 (1961).
7. C. Scholz, *Bull. Seismol. Soc. Amer.* **58**, 399 (1968).
8. N. Warren and G. Latham, *J. Geophys. Res.* **75**, 4455 (1970).
9. Y. Nakamura, C. Veach, B. McCauley, *Research Report ERR-FW-1176* (General Dynamics Corp., New York, 1971).
10. P. Dyal and C. Parkin, *Proceedings of the Second Lunar Science Conference* (M.I.T. Press, Cambridge, 1971), vol. 3, p. 176.
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Mercury in a Greenland Ice Sheet: Evidence of Recent Input by Man

Abstract. *The increased mercury content in a Greenland ice sheet over the last several decades suggests the dissemination of this element about the earth's atmosphere through the activities of man. The mercury content in the atmosphere appears to result primarily from the degassing of the earth's crust. Increased flux may come about as a result of the enhancement of this degassing process through the actions of man.*

Has the flux of mercury from the continents to the atmosphere been influenced measurably by the activities of man? Such processes as the combustion of fossil fuels, the roasting of ores, or the production of chemicals with mercury catalysts could, in principle, compete with other natural phenomena to cause the injection of mercury into the air. The purpose of this investigation was to probe this possibility.

Permanent snowfields record the introduction of matter into the atmosphere. These ices contain in essentially unchanged condition both the water and the accumulated solids that precipitated from the air as a function of time. Thus, it is possible to draw inferences regarding the chemical composition of the atmosphere as it existed centuries and even millennia ago through the analysis of this material, particularly since the various strata are susceptible to reliable dating by a variety of techniques including ^{210}Pb and fission product geochronologies, the isotopic analysis of oxygen, and firn stratigraphy.

Dated glacial samples from Greenland (and a single sample from Antarctica), which had been previously analyzed for their lead (*1*), sulfate (*2*), and selenium (*3*) concentrations, formed the basis of this work. The Greenland samples were from the Camp Century area (77°10′N, 61°07′W) and from a virgin site 80 km east by southeast of this location. The ices were collected by Patterson under extremely careful conditions (*1*). The older samples of the Greenland ice sheet were recovered from the walls of an inclined shaft at Camp Century, and the samples of more recent ages were taken from the walls of open trenches at the virgin site. The single Antarctic sample was recovered from an inclined shaft at the New Byrd Station (80°01′S, 119°31′W). The samples were melted and stored in sealed polyethylene containers in 1966 immediately after removal from the glaciers (*1*).

The mercury content of the glacial ice was determined by thermal neutron activation analysis. Thirteen samples whose total volumes ranged from 200 to 400 ml were analyzed. The water from each sample was introduced directly from the original polyethylene containers into the requisite number of 15-ml polyethylene vials, each of which contained 1 ml of concentrated nitric acid. The vials had been previously immersed in concentrated nitric acid for 16 to 18 hours at room temperature, rinsed subsequently five times with double-distilled water, and rinsed finally with the glacial water.

Three 15-ml vials, each containing 6.00 μg of mercury in 15 ml of 1*N* nitric acid, served as the comparator. Eight vials, each filled with 1*N* nitric acid, constituted a procedural blank, and two vials, each filled with 15 ml of concentrated nitric acid, represented the blank for this reagent. The double-distilled water and nitric acid used for this investigation were from single sources.

All vials were sealed in polyethylene bags and then loaded in stacks of three each in irradiation containers. The three comparator tubes were placed within an individual container at each of the three levels to correct for the vertical variation of the neutron flux within the reactor. The loaded containers were rotated at 1 revolution per minute about the core of the Triga reactor of the Gulf Energy and Environment Service, San Diego, California. All samples were irradiated for 60 minutes in a thermal flux of about 2×10^{12} neutron cm^{-2} sec^{-1}, at a temperature not in excess of 30°C.

Experiments performed at 50°C and a flux of 10^{12} neutron cm^{-2} sec^{-1} demonstrated that mercury radioactivity is lost from plastic containers when irradiations of 12 to 65 hours are carried out (*4*). In our preliminary recovery experiments at the nanogram level, under the experimental conditions of the present study no such loss occurred.

After the irradiation, samples were weighed in tared beakers. A mercury carrier (10 mg) was added to the sample, and the solution was adjusted to *p*H 1 with concentrated ammonium hydroxide. Fresh stannous chloride solution (10 ml), prepared by the addition of about 30 ml of concentrated hydrochloric acid to 10 g of mossy tin, was introduced. The resultant precipitate was collected on a Millipore membrane filter (0.45-μ porosity). The precipitate was subsequently dissolved with 10 to 15 ml of aqua regia, and the solution was neutralized to *p*H 7 with ammonium hydroxide. Hydrogen sulfide gas was bubbled through the solution until a dense black precipitate appeared. The filter membranes containing the mercuric sulfide precipitate were transferred to polyethylene containers for counting.

Table 1. Mercury concentrations in the glacial samples. The sample deposited in 1724 was recovered from Antarctica, the others from Greenland. The sample deposited in the spring of 1965 was analyzed in triplicate, and the error shown gives the average deviation from the mean.

Time of deposition	Mercury content (nanograms per kilogram of water)
800 B.C.	62
1724	75
1815	75
1881	30
1892	66
1946	53
1952	153
1960	89
1964 (fall)	87
1964 (winter)	125
1965 (winter)	94
1965 (spring)	230 ± 18
1965 (summer)	98

The procedural and nitric acid blanks were similarly treated. In the case of the comparators, precipitation with stannous chloride was omitted.

Four days after the irradiation, the 77-kev gamma ray of ^{197}Hg was measured with a NaI(Tl) detector coupled to a pulse-height analyzer. The ^{197}Hg free of other radionuclides was obtained by the third day after the irradiation. A small amount of ^{24}Na, which was carried through with the mercury in the radiochemical purification, had decayed to a concentration below the limit of detection by that time. The accepted half-life of 65 hours for ^{197}Hg was computed from decay data obtained over counting periods of 4 to 8 days.

The procedural and nitric acid blanks were free of detectable quantities of ^{197}Hg. The sensitivity of the measurement, which is defined by a count rate in excess of three standard deviations above the normal background count 4 days after the irradiation, is about 2 ng.

Subsequent to the counting, the HgS was dissolved in 2 ml of aqua regia and diluted to 25 ml with water. The atomic absorptivity of this solution was compared with that of a mercury standard to obtain the carrier yield. The recovery was usually in excess of 90 percent. The average error of a sample analyzed in triplicate (Table 1) is 8 percent.

The mercury contents in glacial materials of different ages from 800 B.C. to A.D. 1965 (Table 1) indicate significantly higher rates of deposition of this element in recent years. Samples from waters deposited prior to 1952 had mercury contents ranging from 30 to 75 ng per kilogram of water with an average value of 60 ± 17. The mercury concentration in waters deposited between 1952 and 1965 averaged 125 ± 52 ng per kilogram of water with a range between 87 and 230.

This increased content of mercury in glacial snows in recent times is probably a reflection of man's impact upon the environment. What activities of human society could be responsible for the added inputs to the atmosphere?

Our approach to this problem is based upon oversimplified models of interactions between the earth's geospheres in which often fragmentary data on the geochemical parameters of mercury are used. Nonetheless, as a consequence of the following argument, we reach the conclusion that the mercury in the atmosphere probably arises predominantly from the degassing of crustal materials and that, if there is a measurable global impact by man upon the atmospheric burden of mercury, it may be through an enhancement of this degassing process.

The mercury content of unpolluted air appears to span the range of less than 1 to 10 ng/m^3 (*5*). If we use a value for the mercury content of 1 ng/m^3, and take the density of the atmosphere to be 1.3×10^3 g/m^3 and the weight of the atmosphere to be 5.1×10^{21} g, the atmospheric burden of mercury is 4×10^9 g. Rain effectively washes mercury from the atmosphere (*6*). If we take an average time between rains of 10 days, the flux of mercury from the continents to the atmosphere is 1.5×10^{11} g/year.

This calculation can be checked in the following way. The annual precipitation of the world is 4.2×10^{17} liters. The average content of mercury in the rainwater of the 1930's is 0.2 part per billion (ppb) (*6*). The flux of mercury from the atmosphere to the continents is 8.4×10^{10} g/year. If a mercury content of 0.06 ppb for apparently uncontaminated glacial ice (Table 1) is used, the flux is about 2.5×10^{10} g/year. The rate of exchange of mercury between the air and the solid surface of the earth appears to be in the range from 2.5×10^{10} to 1.5×10^{11} g/year.

The flux of mercury from the continents to the oceans by way of the rivers is much less than that of the continents to the atmosphere. If we use a value of 38×10^{15} liters as the annual river and ice-cap runoff and an upper limit of 0.1 ppb of mercury in rivers (*7*), an upper limit of transfer of 3.8×10^{9} g of mercury per year is obtained.

The amount of mercury produced throughout the world in 1968 was 8.8×10^{9} g. A substantial loss of mercury to the atmosphere occurs in chlor-alkali production, and about one-third of the mercury consumed annually in the United States is used in that process (*8*). If we apply this factor of $\frac{1}{3}$ to the world consumption, the resultant flux is 3×10^{9} g/year, a fraction of the flux involved in the degassing process.

On the basis of recent data on fossil fuel combustion, it has been computed that an upper limit of 1.6×10^{9} g of mercury per year can be released to the environment through the burning of coal, oil, and lignites (*9*). Other industrial activities yield potential atmospheric fluxes of this order of magnitude. The amount of cement produced throughout the world in 1960 was 33×10^{13} g. Since cement, during its production, is heated to temperatures of 1400° to 1500°C, the mercury release from the limestone and shale components of the raw materials could conceivably discharge significant quantities of mercury to the environment. Since the mercury content of shales clusters around several hundred parts per billion and since the mercury content of limestones is usually less than 100 ppb, an upper limit of 300 ppb is taken as a conservative estimate of the mercury content of the building materials for cement. Thus, cement manufacture might result in the release of 10^{8} g of mercury per year. Perhaps the roasting of sulfide ores releases significant quantities of mercury to the environment. Such mining operations involve 2×10^{14} g of ore per year (*10*). But even with a mercury content of 10 parts per million, this flux is only 2×10^{9} g/year. Hence, a survey of industrial activity has not revealed mercury releases to the atmosphere that can rival that of the natural degassing rate, estimated to range between 2.5×10^{10} and 1.5×10^{11} g/year.

The following explanation is proposed to account for the doubling of the mercury content in a Greenland ice sheet. The background concentration of mercury in the atmosphere arises from the degassing of the upper mantle and lower crust. This view is supported by the observations that the mercury is markedly enriched in sediments as compared to igneous rocks (*11*). Moreover, the atmospheric mercury concentration is a function of barometric pressure (*6*). Increased exposure of such crustal materials can result in increased fluxes of mercury to the atmosphere. The variety of activities of man that result in greater exposure of the earth's crust through alteration of terrestrial surfaces allows more mercury vapor and more gaseous compounds to enter the atmosphere.

In conclusion, the recently measured mercury concentrations in such pelagic fish as tuna and swordfish are probably not far removed from the norm. The input of twice as much mercury to surface waters of the ocean in recent times can only increase the amount of mercury in the lower trophic levels by, at best, a factor of 2.

This argument can be approached in another way. There are 10^{12} g of mercury in the mixed layer of the ocean, if we assume a depth of 100 m and an average mercury content of 30 ng/liter. The increased mercury flux, 1.5×10^{11} g, presumed to result from an enhancement of earth degassing, would add annually only 15 percent to the mercury burden of this water body. With a residence time of mercury in this layer of as much as 5 years, the mercury content would be augmented by a factor of only 0.75. The increased mercury content in surface waters, if transmitted through the food web to such upper trophic levels as those of the swordfish and tuna, would, at best, double the mercury contents in these organisms.

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References and Notes

1. M. Murozumi, T. J. Chow, C. C. Patterson, *Geochim. Cosmochim. Acta* **33**, 1247 (1969).
2. M. Koide and E. D. Goldberg, *J. Geophys. Res.* **76**, 6589 (1971).
3. H. V. Weiss, M. Koide, E. D. Goldberg, *Science* **172**, 261 (1971).
4. L. C. Bate, *Radiochem. Radioanal. Lett.* **6**, 139 (1971).
5. M. Fleischer, *U.S. Geol. Surv. Prof. Pap. 213* (1970), p. 6.
6. J. H. McCarthy, Jr., J. L. Meuschke, W. H. Ficklin, R. E. Learned, *ibid.*, p. 37.
7. R. L. Wershaw, *ibid.*, p. 29.
8. *Mineral Industry Surveys* (U.S. Bureau of Mines, Washington, D.C., 1970).
9. K. K. Bertine and E. D. Goldberg, *Science* **173**, 233 (1971).
10. L. J. Shannon, A. E. Vandegrift, P. G. Gorman, *Midwest Res. Inst. Rep. MRI-1023* (1971).
11. K. H. Wedepohl, abstract of the International Geochemical Congress, Moscow, 20–25 July 1971, p. 936.
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Viral RNA Polymerases: Electron Microscopy of Reovirus Reaction Cores

Abstract. *The Kleinschmidt technique has been used to observe reovirus cores that have synthesized messenger RNA. Some individual viral cores probably synthesize all ten messenger RNA molecules in vitro. Each messenger RNA molecule appears to be attached to a different site on the core surface, implying that there are probably a number of different enzymic sites in each core.*

Virus particles that contain enzymes capable of transcribing the viral genetic information have been subjected to intensive biochemical study. Reovirus (*1*, *2*), vaccinia virus (*3*), influenza virus (*4*), vesicular stomatitis virus (*5*), and the RNA tumor viruses (*6*), contain enzymes of this type. These enzyme activities are usually studied by measuring the incorporation of labeled ribo- or deoxyribonucleoside triphosphates into the acid-insoluble product synthesized by the enzyme. This provides a sensitive and convenient method for characterizing the average product synthesized in vitro by the viral cores or nucleoids. However certain aspects of the mechanism of action of these enzymes are not readily investigated by these methods—for example, an assessment of the number of sites at which nucleic acid is synthesized.

We report here experiments designed to make possible electron microscopic observation of RNA transcription in vitro. Reovirus cores have been used as an experimental model because the core contains a very active RNA tran-