more distant origin in the Caribbean is also possible in view of the fact that serpentinite deposits exist in Cuba, Hispaniola, and Puerto Rico. Furthermore, stoneworking and seafaring skills were well developed in the Antilles long before contact with Europe occurred (*12*). This report suggests alternative sources of raw materials for the pendants. However, our data are still insufficient to throw light on the interesting problems related to the transport of winged pendants within northern South America, Central America, and the Caribbean area.

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References and Notes

1. E. Wagner, in preparation.
2. E. Wagner, *Inst. Venez. Invest. Cient. Bol. Inform. Dep. Antropol. No. 4* (1966), p. 30.
3. ———, *Yale Univ. Publ. Anthropol. No. 71* (1967), p. 53.
4. I. Rouse and J. M. Cruxent, *Venezuelan Archaeology* (Yale Univ. Press, New Haven, 1963), pp. 17–22.
5. M. A. Tamers, *Radiocarbon* **8**, 206 (1966).
6. E. Wagner, *Acta Cient. Venez.* **21**, 180 (1970).
7. M. A. Tamers, *Radiocarbon* **11**, 403 (1969); *ibid.* **12**, 513 (1970).
8. R. H. Jahns, in *Ultramafic and Related Rocks*, P. J. Wylie, Ed. (Wiley, New York, 1967), p. 149.
9. C. Balser, in *Essays in Pre-Columbian Art and Archaeology*, S. K. Lothrop *et al.*, Eds. (Harvard Univ. Press, Cambridge, 1961), p. 210; W. C. Bennett, *Anthropol. Pap. Amer. Mus. Natur. Hist.* **36**, 123 (1937); M. Briceño Iragorry, *Ornamentos fúnebres de los aborígenes del Occidente de Venezuela* (Tipografía Vargas, Caracas, 1928), pp. 7–21; A. Ernst, *Z. Ethnol.* **17**, 126 (1885); H. Feriz, *Zwischen Peru und Mexico* (Koninklijk Instituut voor de Tropen, Medeedeling, Amsterdam, 1959); E. H. Giglioli, *Int. Congr. Americanists Proc.*, session 16, part 2 (1908), p. 321; E. Kennedy Easby, *Pre-Columbian Jade from Costa Rica* (Emmerich, New York, 1968); S. K. Lothrop, *Peabody Mus. Amer. Archaeol. Ethnol. Mem.* **7**, 163 (1937); J. A. Mason, *Anthropol. Ser. Field Mus. Natur. Hist.* **20**, 179 (1936); G. Reichel-Dolmatoff and A. Reichel-Dolmatoff, *Revista Colomb. Antropol.* **4**, 189 (1955); G. Reichel-Dolmatoff, *Colombia* (Thames and Hudson, London, 1965), pp. 142–168.
10. F. J. Turner and J. Verhoogen, *Igneous and Metamorphic Petrology* (McGraw-Hill, New York, ed. 2, 1960), pp. 307–321.
11. C. Martin, B. Bellizzia, A. Bellizzia, *Bol. Geol. Dir. Geol. (Venezuela)* **8**, 273 (1967).
12. I. Rouse, *Science* **144**, 499 (1964).
13. R. Weyl, *Die Geologie Mittelamerikas* (Borntraeger, Berlin, 1961), figure 64; *Geotek. Forsch.* No. 23 (1966), figure 11; *Geologie der Antillen* (Borntraeger, Berlin, 1966), figures 6, 23, 37, and 55; A. Bellizzia, *Bol. Geol. Dir. Geol. (Venezuela)* **8**, 159 (1967); Instituto Nacional de Investigaciones Geológico-Mineras (Colombia), "Geological Reconnaissance Map of the Sierra Nevada de Santa Marta, Colombia" (1969); C. Schubert and P. Moticska, *Trans. Caribbean Geol. Conf. 6th* (Porlamar, Venezuela, in press).
14. We thank J. P. Lockwood for providing samples of serpentinites from Guajira Peninsula, Compañía Shell de Venezuela for preparing thin sections, and C. Quintero for drawing Fig. 1B. The serpentinite localities of the Guajira Peninsula (Fig. 1A) were derived from theses (Princeton University, Princeton, N.J.) by J. P. Lockwood (1965), W. D. MacDonald (1964), and W. Alvarez (1967).

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Lead-212 in the Urban Boundary Layer of New York City

Abstract. *The radioactive emanation product lead-212 is useful in estimating rates of air exchange within the urban boundary layer. The concentration of lead-212 is negligible in air of oceanic origin as well as in air above continental areas under snow cover. On several days when conditions were such that one of these types of air mass approached New York City, measurements were made which show that the source strength of lead-212 within the city is relatively constant. On two such days vertical profiles of the concentration of lead-212 were measured from the Empire State Building, which served as a sampling tower. From the data of these profiles and a two-layer model of the urban boundary layer, we estimate the vertical eddy diffusivity to be of the order of tens of square meters per second and the residence time of air within the street layer to be of the order of 5 minutes. These results are consistent with the observed distribution of stable lead and with an independent estimate of the eddy viscosity from a wind profile. Under moderate wind conditions and with a mixing depth of hundreds of meters, virtually all the horizontal transport of lead-212 and other tracers with street-level sources takes place in the advective layer.*

The level of air pollution in a city depends greatly on the rates of mixing and renewal of the air within the urban boundary layer. Patterns of air flow at street level are so complicated that it is impossible to estimate the renewal rate of air by direct measurements of the wind field and temperature profiles. The exchange rates of air must therefore be measured by tracer techniques.

The emanation products of the noble gas radon and thoron and their daughters (*1*) provide a set of natural radioactive tracers that are applicable to this problem because they are easy to measure experimentally (*2*, *3*), are produced over all continental areas, and the theory of their transport has been developed (*4*, *5*). In this report the utility of ^{212}Pb, a daughter product in the thoron chain, is emphasized because its half-life (10.6 hours) is sufficiently short that it should respond to local and diurnal meteorological conditions and sufficiently long that it should reflect average exchange conditions on an urban scale. Also, it is present on particles small enough to respond to air mass movements. New York City is appropriate for testing the utility of this radioisotope because it is adjacent to the Atlantic Ocean. In general, emanation products from oceanic areas are negligible compared to those from continental areas, and this is particularly true of the thoron chain. Thus when an air mass of oceanic origin (a southeast wind in the case of New York) approaches the city, the ^{212}Pb source characterstics of the city itself can be directly measured.

Measurements were made of the concentrations of ^{212}Pb, particulates, ^{222}Rn, and in some cases total particulate lead (*6*). Appropriate meteorological data were obtained from the U. S. Weather Bureau. Our preliminary results suggested that a two-layer mathematical model could be used for treating air transport and exchange within the urban boundary layer, and the results are discussed in this context. We realize that the real urban situation is more complex than that portrayed by such a simple model, but we believe that the lack of vertical resolution in our sampling precludes the use of a more complicated model. Figure 1 shows the four sampling sites in New York City's Borough of Manhattan, their geographic

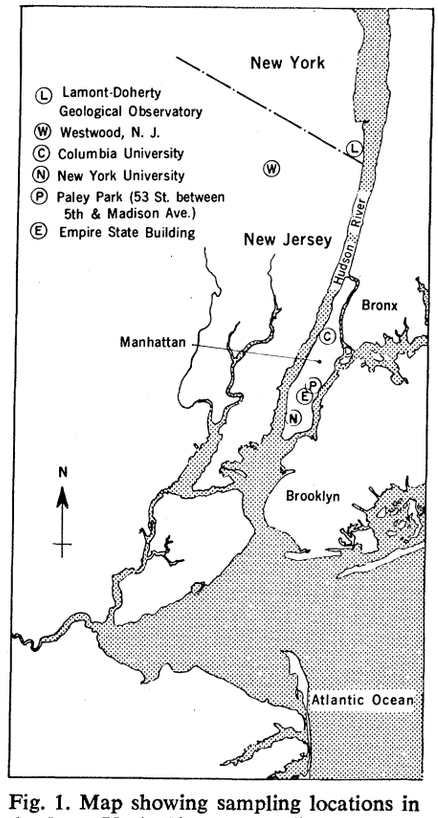

Fig. 1. Map showing sampling locations in the New York City metropolitan area.

relation to the surrounding continental area, and their proximity to the ocean.

Table 1 presents ^{212}Pb concentrations at three sampling sites, including Lamont-Doherty Geological Observatory, Palisades, New York. Most of these samples were taken on dates on which either the air mass was of oceanic origin or the region surrounding the New York area was under snow cover. It has been shown that exhalation of thoron is extremely reduced by snow cover (*7*). The significant result here is that these concentrations are all low (less than 0.33 pc/m^3) compared with concentrations (up to 1.5 pc/m^3) measured when the air mass was of continental origin and there was no snow cover [see Table 1 (spring 1970) and Fig. 2].

Figure 2 presents a sequence of ^{222}Rn, ^{212}Pb, and dust profiles at the New York University campus in downtown Manhattan (8th Street near Broadway) during May and June 1970. The 12th floor, about 50 m high, is at the approximate mean roof level of the buildings in that area. The ^{222}Rn concentration was significantly lower on 26 May, when the wind was from the ocean (southeast), than on other days, and in all cases the concentration was uniform with height up to about 50 m. The ^{212}Pb concentration varied by about a factor of 4 during the sampling period and was lowest on 26 May, when the air mass was oceanic in origin. The values were also low the next day, when the wind was from the northwest, but on 26 and 27 May almost the entire eastern half of the United States received significant precipitation, and we attribute the low concentration on 27 May to reduced thoron exhalation (*8*). Except for one day (8 June) there was no significant variation of ^{212}Pb concentration with height. Dust concentrations varied significantly and were generally lowest in the early morning hours, apparently during the hours of lowest traffic and other activity. The dust concentration on 26 May was also low in the early evening, but this was believed to be due to precipitation during that day.

To measure air exchange rates it was necessary to obtain samples above the city's mean roof levels. The Empire State Building is an excellent sampling tower for this purpose. Figure 3 presents profiles of the concentrations of ^{212}Pb, ^{222}Rn, dust, and stable lead in samples taken at several levels outside the Empire State Building on 26 February and 19 March 1971. On both days the ^{222}Rn concentration was low and the wind was from the southeast. A uniform vertical concentration of ^{222}Rn is observable on both days; while this is also noted in Fig. 2, the vertical scale of the profiles in Fig. 3 is almost an order of magnitude greater. This indicates that the city itself is not the source of the measured ^{222}Rn. Lead-212, stable lead, and dust concentrations, all associated with particulate aerosol and with ground-level sources, decrease with height. The absolute concentrations of ^{212}Pb at ground level under the oceanic regimes of 26 February and 19 March 1971 were similar to each other and within the range of concentrations listed in Table 1 for oceanic-air regimes or regimes of continental air over snow cover.

What conclusions can be dawn from these results concerning the suitability of ^{212}Pb for studies of urban air pollution and for model calculations?

Table 1. Lead-212 concentrations and wind directions. Lead-212 concentrations at street level at Columbia University in New York City and at Lamont-Doherty Geological Observatory (L-DGO) during the winter of 1970 are compared with those at Paley Park during the spring of 1970. The low winter concentrations are attributed to a considerable snow cover that persisted over much of New York and New Jersey. Concentrations during spring and summer drop to low values only under oceanic air conditions (see Figs. 2 and 3). Wind velocities are given in miles per hour (1 mph = 0.447 m/sec).

Date	Time	Location	Wind direction (deg)/velocity (mph)	^{212}Pb (pc/m^3)
		Winter 1970		
20 January	1718–1918	L-DGO	10/7	0.070
22 January	1600–1830	Columbia	320/12	0.080
27 January	0016–0117	Columbia	310/7	0.085
29 January	1115–0315	Columbia	220/10	0.090
2 February	2330–0330	L-DGO	180/13	0.026
2 February	1915–2011	L-DGO	180/13	0.020
2 February	2330–0330	Columbia	170/14	0.200
4 February	2345–0345	Columbia	320/16	0.09
10 February	2340–0340	Columbia	70/12	0.25
12 February	2330–0300	Columbia	280/15	0.17
16 February	2300–0315	Columbia	300/7	0.19
17 February	2315–0300	Columbia	60/9	0.33
18 February	2300–0300	Columbia	120/7	0.22
22 February	1300–1500	Columbia	230/14	0.69
22 February	1800–2000	Columbia	230/14	0.22
22 February	2300–0300	Columbia	230/14	0.17
23 February	1300–1700	L-DGO	290/17	0.02
		Spring 1970		
30 April	0950–1207 (4 samples)	Paley Park	100/8	0.24–0.33
8 May	0828–1255 (8 samples)	Paley Park	230/6	0.99–1.05

Table 2. Transport parameters for ^{212}Pb in New York City. The data were obtained from samples taken outside the Empire State Building in 1971.

Parameter	Units	26 February	19 March
H, mixing depth*	m	910†	1300
U_a, horizontal velocity in the advective layer*	m/sec	7.7†	11.5
C_s, ^{212}Pb concentration, at street level	pc/m^3	0.18	0.14
$\tilde{C}$, ^{212}Pb concentration per unit area above the city at the Empire State Building	pc/m^2	83‡	60§
F, horizontal flux of ^{212}Pb downwind from the Empire State Building	pc m^{-2} sec^{-1}	0.0285	0.0300
$\lambda\tilde{C}$, radioactive decay	pc m^{-2} sec^{-1}	0.0015	0.0010
$\tilde{S}$, source strength (flux plus decay)	pc m^{-2} sec^{-1}	0.0300	0.0310
K, vertical eddy diffusivity	m^2/sec	37	48
τ_s, residence time of air in the street layer	sec	300	230

* Data obtained from the U.S. Weather Bureau. † Afternoon data estimated by the U.S. Weather Bureau from morning data. ‡ Based on the third ^{212}Pb profile (Fig. 3), which was taken after the disappearance of the inversion. During the third profile the temperature was 8.9°C at the 30th floor and 6.1°C at the 86th floor. § Based on an average of both ^{212}Pb profiles, during which the lapse rate was approximately adiabatic, that is, 1°C per 100 m and 2°C per 100 m.

The concentration of ^{212}Pb does not display as much diurnal or vertical variation as does the dust concentration (Fig. 2). Therefore, although present in the urban atmosphere in particulate form, ^{212}Pb is not significantly removed by gravitational settling or by deposition on boundary interfaces (*3*); that is, its primary sink is radioactive decay.

The fact that we did not find a difference in the ^{212}Pb concentration between day and night (Fig. 2) suggests that ^{212}Pb is not produced by urban activities but is continuously emitted from the ground and probably from building materials. Some direct measurements have been made to test this hypothesis (*9*).

In two samples taken well above the mean roof levels, that is, at the top of the Empire State Building, the concentration of ^{212}Pb was about half of the concentration at street level. This means that the vertical flux of ^{212}Pb up from its source near street level was very effective (*10*).

Now consider the urban boundary layer as divided into the street layer (up to the height of the average roof level) and the advective layer (the layer between the average roof level and the top of the mixing layer), as shown in Fig. 4. The following discussion will be in terms of this two-dimensional, two-layer transport model, in which it is assumed (i) that horizontal transport in the y direction is negligible, (ii) that the wind field in the advective layer above the city is regular with respect to velocity and direction and can be approximated from radiosonde data, and (iii) that the source distribution of thoron (and its daughter ^{212}Pb) is horizontally uniform. The horizontal flux thus has two regimes, that within the street layer and that in the advective layer (subscripts s and a, respectively) (*11*),

$$F_s = \frac{1}{X}\int_0^{H_s} C_s U_s dz \qquad (1)$$

$$F_a = \frac{1}{X}\int_{H_s}^{H} C_a U_a dz \qquad (2)$$

where F is the flux (pc m^{-2} sec^{-1}), X is the horizontal dimension of the city upwind from the sampling point to the coast (m), U is the wind velocity (m/sec), C is the concentration of ^{212}Pb (pc/m^3), and H is the mixing depth (m).

To gain an idea of the relative importance of F_s and F_a we use the data of 19 March 1971. To be conservative we assume U_s, the horizontal wind velocity in the street layer, to be the mean surface-wind velocity of 7 m/sec measured at La Guardia Airport on 19 March 1971. Assuming that H_s is 50 m and X is 20 km,

$$F_s = 2 \times 10^{-2} \text{ pc m}^{-2} \text{ sec}^{-1}$$

For U_a and H estimated from the noon radiosonde at La Guardia and C_a calculated from the exponential rate of decrease of the concentration of ^{212}Pb from average of both profiles,

$$F_a = 30 \times 10^{-2} \text{ pc m}^{-2} \text{ sec}^{-1}$$

Thus, F_s is less than 10 percent of F_a In fact, F_s must have been even smaller because of the distortion of the wind field by the city; that is, 7 m/sec is probably an upper limit to the value of U_s. On 19 March (and 26 February), therefore, F_a was much greater than F_s. That is, more than 90 percent of the transport of ^{212}Pb away from the city occurred within the advective layer. This was also true for stable lead, as it presented a similar vertical distribution.

The balance equation for the advective layer can be written

$$-K_z \left\langle \left(\frac{dC_a}{dz}\right)_{z=H_s} \right\rangle = \lambda < \tilde{C}_a > + F_a \qquad (3)$$

where $\tilde{C}_a$ is the concentration above a unit area (pc/m^2), K_z, is the vertical diffusion coefficient (m^2/sec) (assumed

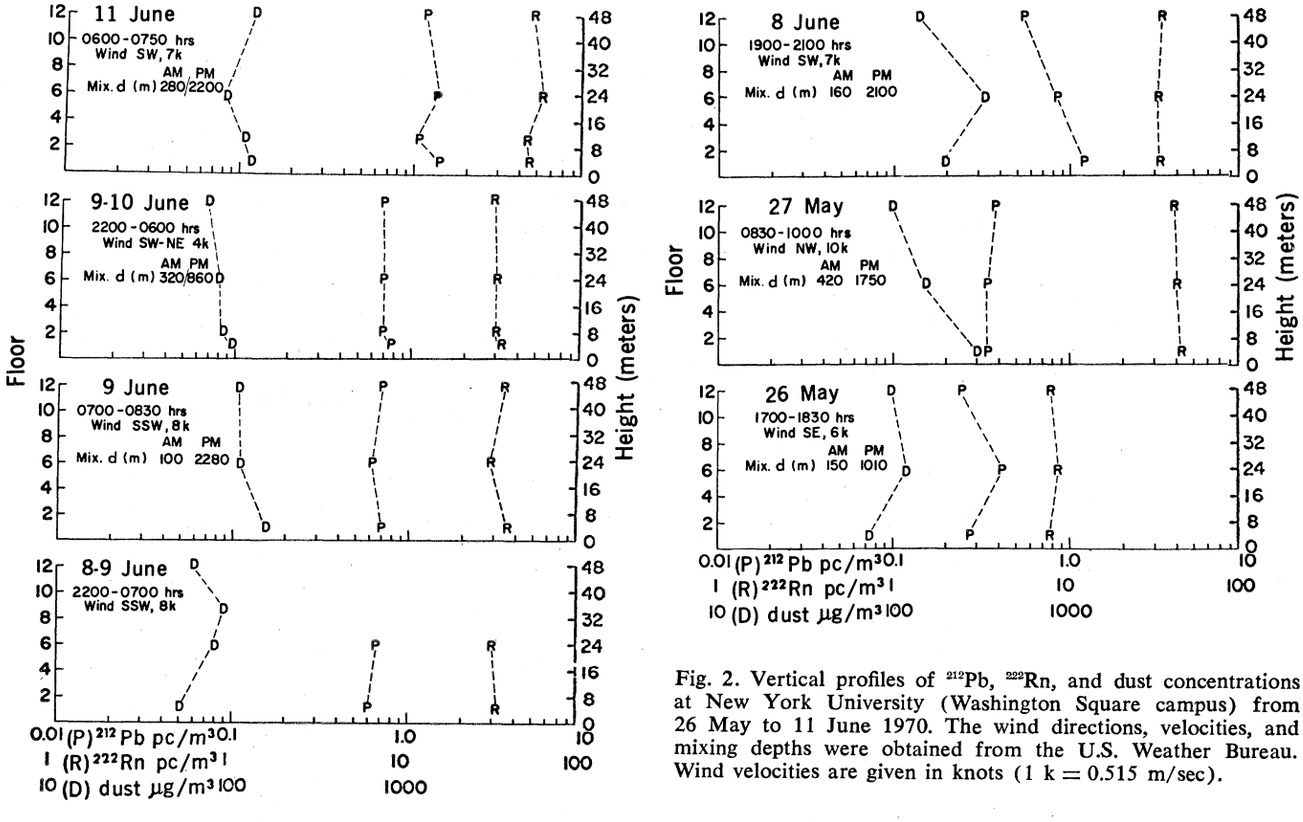

Fig. 2. Vertical profiles of ^{212}Pb, ^{222}Rn, and dust concentrations at New York University (Washington Square campus) from 26 May to 11 June 1970. The wind directions, velocities, and mixing depths were obtained from the U.S. Weather Bureau. Wind velocities are given in knots (1 k = 0.515 m/sec).

constant over the X dimension), and $< >$ indicates the average over the horizontal dimension of the city (X in Fig. 4). We can approximate the vertical eddy diffusivity, K_z from Eq. 3 by using the data from the Empire State Building and assuming that the mean vertical gradient of the ^{212}Pb concentration between the building and the shore was half of that measured. That is, because we expect the ^{212}Pb concentration of oceanic air to be almost zero, the vertical gradient at the coastline is large, and we assume a regular decrease in the gradient between the coast and the sampling point (schematically shown in Fig. 4). The fact that the gradient did not change much in all five profiles on 26 February and 19 March, despite differences in wind velocity and mixing depth, substantiates this assumption.

The mean source strength can be estimated

$$\langle \tilde{S} \rangle = \lambda \langle \tilde{C} \rangle + F \text{ pc m}^{-2} \text{ sec}^{-1} \quad (4)$$

where F can be approximated as F_a (see above). On a volume basis

$$\langle \bar{S} \rangle = \frac{\langle \tilde{S} \rangle}{H_s} \text{ pc m}^{-3} \text{ sec}^{-1} \quad (5)$$

Using Eqs. 3 and 4, the data for wind velocity and mixing depth from the U.S. Weather Bureau and the data of Fig. 3, we compute the results presented in Table 2. The estimates of eddy diffusivity calculated in this way are of the order of tens of square meters per second. For comparison we estimate an eddy viscosity of about 25 m^2/sec from the U.S. Weather Bureau radiosonde (*12*). Note that similar estimates of $\langle \tilde{S} \rangle$ were obtained on both days. We suggest that the small range of ^{212}Pb concentrations at street level (Table 1) when the air mass was of oceanic origin or the region surrounding New York was under snow cover (i) proves that the measured ^{212}Pb was of local origin, that is, originated within the city, and (ii) further suggests that the source strength of ^{212}Pb parent (thoron) is fairly constant despite some variability in meteorological conditions. The moisture content of the soil is the most important factor in the variability of radon and thoron exhalation from soil (*8*). We suggest that this control may be less important in the city, with its high surface area of cement, asphalt, and other low-porosity building materials, and that this accounts for the apparent constancy in source strength.

The concept of mean life or residence time is generally expressed by $\tau = V/Q$ (in seconds), where V is the reservoir volume (m^3) and Q is the flow rate into or out of the reservoir (m^3/sec). This concept is usually applied to interactions between homogeneous reservoirs in box models. Our results indicate that the street layer, but not the advective layer, may be regarded as a well-mixed reservoir. If, however, we regard the air in the advective layer as a medium of interaction between the street layer and any well-mixed air mass approaching the city, the balance equation for any tracer will be

$$Q(\langle \tilde{C}_o \rangle - \langle \tilde{C}_s \rangle) + \langle \tilde{S} \rangle V_s - \lambda \langle \tilde{C}_s \rangle V_s = 0 \quad (6)$$

where $\langle \tilde{C} \rangle_0$ is the mean concentration of the tracer above a unit area in the air mass upwind of the city (pc/m^2). The residence time, which in this case is a measure of the interaction between the air in the street layer and the approaching air mass, is given by

$$\tau_s = \frac{V_s}{Q} = \frac{\lambda(\langle \tilde{C}_s \rangle - \langle \tilde{C}_o \rangle)}{\langle \tilde{S} \rangle - \lambda \langle \tilde{C}_s \rangle} \quad (7)$$

where $\langle \tilde{S} \rangle$ is given by Eq. 4. When oceanic air approaches the city or the continental fetch is under snow cover, $\langle \tilde{C}_0 \rangle = 0$.

Thus, to the degree that the source strength, $\langle S \rangle$, is constant and the air mass approaching the city contains a neglible amount of ^{212}Pb, one can obtain a measure of vertical mixing in the street layer from a single measurement of ^{212}Pb concentration. In the case of New York City, these conditions obtain relatively infrequently, that is, during southeasterly winds and when the surrounding areas is covered by snow. For cities where an oceanic air mass is more common, for example, San Francisco, Los Angeles, and San Diego, an

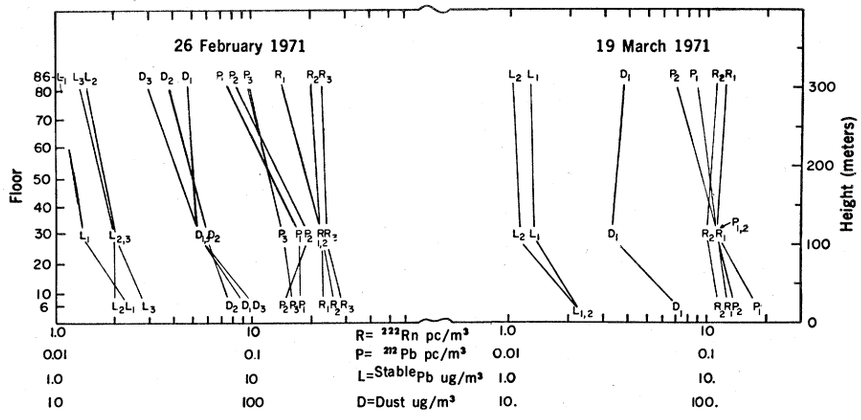

Fig. 3. Vertical profiles of ^{212}Pb, ^{222}Rn, dust, and stable lead concentrations in samples taken at the Empire State Building on 26 February and 19 March 1971.

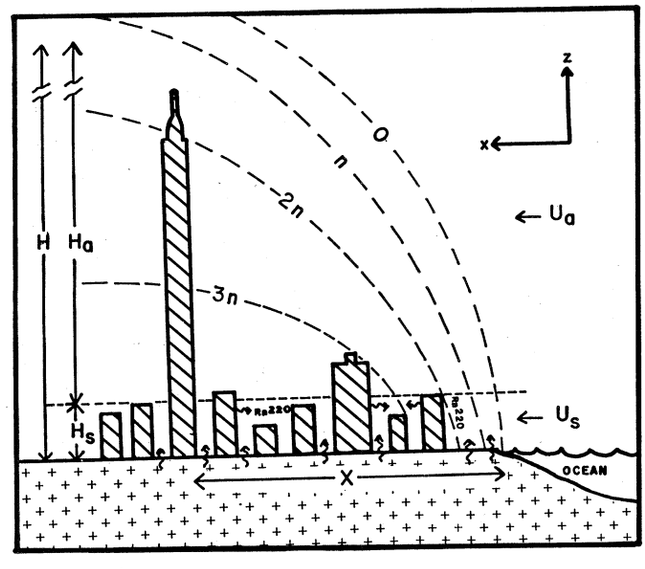

Fig. 4. Schematic diagram of New York City illustrating the two-layer transport model in which the mixing layer H is divided into the street layer and the advective layer at the height of the mean roof level. The isopleths show that the concentration of ^{212}Pb in the air is zero at the coastline and increases going inland. Note that the distribution is not homogeneous within the street layer near the coastline but it rapidly becomes homogeneous in the downwind direction.

estimate of vertical mixing from a single measurement of ^{212}Pb may be possible more often. When such ideal conditions do not obtain, the residence time can still be estimated from Eq. 7, provided C_0 is vertically homogeneous and known. On the 2 days for which we have measurements, similar estimates of τ_s were obtained, of the order of 4 to 5 minutes. If our conclusion is correct, that the source strength of the city's ^{212}Pb is relatively constant, then the residence times in the street layer calculated from measurements made on 16 additional occasions during different seasons did not vary by more than a factor of 3 from these values.

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References and Notes

1. The radon chain, with half-lives given in parentheses, is ^{222}Rn (3.8 days), ^{218}Po (3 minutes), ^{214}Pb (27 minutes), ^{214}Bi (19 minutes), ^{214}Po (164 μsec), long-lived isotopes. The thoron chain is ^{220}Rn (54 seconds), ^{216}Po (0.1 second), ^{212}Pb (10.6 hours), ^{212}Bi (1 hour).
2. C. R. Husler and L. B. Lockhart, *J. Geophys. Res.* **70**, 4537 (1965).
3. J. R. Gat and G. Assaf, *Science* **159**, 977 (1968).
4. G. Assaf, *Tellus* **21**, 820 (1969).
5. M. Beran and G. Assaf, *J. Geophys. Res.* **75**, 5279 (1970).
6. Air was pumped for a period of 1 to 10 hours through Gelman type A fiber glass filters, 5 inches (12.7 cm) in diameter, at flow rates of 10 to 18 ft^3/min (1 ft^3/min = 0.028 m^3/min), calibrated with a New York University calibration system with an accuracy of $\pm$ 5 percent. The dust collected on the filters was measured by weighing the filters under controlled temperature and humidity conditions before and after sampling. The filters were counted with a 5-inch diameter, 2π, alpha-scintillation counter. The alpha-counter was calibrated by measuring the radon in air by an independent method [see W. S. Broecker, in *Symposium on Diffusion in Oceans and Fresh Waters* (Lamont-Doherty Geological Observatory, Palisades, N.Y., 1964), pp. 116–145]. In the decay analysis it was assumed that ^{222}Rn and ^{212}Pb were in equilibrium with their descendants and precursors, respectively. The concentration of total lead was measured by atomic absorption spectrophotometric analysis of the dissolved filters.
7. B. I. Styro and T. N. Nedvetskate, *Izv. Acad. Sci. USSR Atmos. Oceanic Phys.* **5**, 501 (1970).
8. D. Guedalia, J. L. Laurent, J. Fontaen, D. Blanc, A. Druilhet, *J. Geophys. Res.* **75**, 357 (1970).
9. On 24 February 1970 we measured a ^{212}Pb concentration of 3.3 pc/m^3 inside a closed garage in Westwood, New Jersey, and 0.7 pc/m^3 outside the garage. The garage was built of wood and had a cement floor. On 10 June 1970 we measured 1.1 pc/m^3 inside a New York University lecture hall, compared with 0.6 pc/m^3 outside. These measurements indicate that buildings are generally sources of thoron, which eventually decays to ^{212}Pb in the urban boundary layer.
10. It is possible that the Empire State Building itself affects the flow of air around it and therefore locally affects vertical mixing. We think that this effect was negligible, as our sampling sites were on the upwind side of the building. In addition the presence of an inversion, detectable at the sampling sites during profiles 1 and 2 on 26 February, argues against vertical mixing induced by the building itself. The U.S. Weather Bureau morning radiosonde at La Guardia airport detected an inversion at 170 m; we found this between the 30th and 86th floors of the Empire State Building, when the temperatures were 10.6°C and 12.5°C, respectively.
11. We consider only the advective flux, which is generally much greater than the diffusive flux (*4*).
12. The wind sounding at La Guardia airport was given by the U.S. Weather Bureau for 19 March at 100-m intervals. It was 7 m/sec from 130° (surface), 9 m/sec from 137° (100 m), and 11 m/sec from 140° (200 m), 13 m/sec from 144° (300 m), 13.5 m/sec from 151° (400 m), and 14 m/sec from 159° (500 m). The geostrophic wind was 16 m/sec from 180° (800 m). The wind profile on that day thus resembled an Ekman spiral, and we applied Lettau analysis [see H. Lettau, *Tellus* **2**, 125 (1950)] to obtain an estimate of the eddy viscosity for the layer between the surface and 400 m. The equation for the eddy viscosity is $K_m = (1/\rho)\,(|T|/|dv/dz|)$, where T is the wind stress vector, z is the horizontal wind vector, and ρ is the density. From the estimated wind stress at 200 m (5 dyne/cm^2) and the wind shear between the surface and 400 m (0.02 sec^{-1}) we calculate 25 m^2/sec for K_m.
13. Supported by AEC contracts AT (30-1) 2663 and AT (30-1) 4055. We are grateful to Dr. M. Bender for taking some of the samples, to G. Mathieu for analyses of stable lead, and to Drs. W. Van Pelt and T. Kneip for the volume calibration of our air samplers. We thank Drs. W. Broecker and J. Friend for helpful discussions and criticisms, Mr. Kussman and Mr. Heidelberger of the U.S. Weather Bureau for meteorological data, and T. Sullivan and his staff at the Empire State Building for permission and assistance in taking samples. Lamont-Doherty Geological Observatory contribution No. 1769.

13 August 1971; revised 27 September 1971

Breakup of Pangaea and Isolation of Relict Mammals in Australia, South America, and Madagascar

Abstract. *The composition of aboriginal land mammal faunas in Australia and New Guinea (prototherians and metatherians), South America (metatherians and eutherians) and Madagascar (eutherians only) is reconsidered in light of continental drift reconstructions of Mesozoic-Tertiary world paleogeography. It is proposed that these three faunas represent successively detached samples of the evolving world mammal fauna as it existed when each of these land masses became faunally isolated from the rest of the world as a result of the progressive fragmentation of Pangaea. Isolation of aboriginal prototherians and metatherians in Australia and New Guinea may date from the Upper Jurassic–Lower Cretaceous; isolation of aboriginal metatherians and eutherians in South America may date from the Middle Cretaceous–Upper Cretaceous; isolation of aboriginal eutherians in Madagascar may date from the Paleocene-Eocene.*

For more than a century zoogeographers have been intrigued by the fact that primitive mammals tend to be concentrated in three widely separated regions in the Southern Hemisphere—Australia and New Guinea, South America, and Madagascar (*1*, pp. 82, 287). Currently, the most widely accepted interpretation of this distribution is that it is a coincidental result of three independent episodes of "sweepstakes dispersal" across past or present water gaps with world continents and islands assumed to have been fixed in their present positions, at least during the time of dispersal of these groups of mammals (*2*, pp. 88–105; *3*, pp. 363, 522). However, the assumption that continental positions have remained fixed during this period is being called in question by a growing body of geophysical research on plate tectonics. Reexamination of relevant faunal evidence in light of new paleogeographic perspectives that are provided by the continental drift reconstructions of Dietz and Holden (*4*) suggests that the distribution of relict mammals in the Southern Hemisphere is not the result of coincidence, but instead that there is a direct causal relation between the early separation of continental masses and the preservation of these relict mammal faunas (Table 1).

According to Dietz and Holden (*4*, pp. 4943–4952) and many other students of continental drift, at the close of the Paleozoic all of the earth's crust was united to form a single supercontinent, Pangaea (Fig. 1A). Near the end of the Triassic, Pangaea began to split into two parts: (i) Laurasia–West Gondwana, which includes present-day North America, South America, Eurasia (excluding India), and Africa, and (ii) East Gondwana, which includes present-day Antarctica, India, Australia, New Guinea, and New Zealand (Fig. 1B). At about the same time, India began to separate from the rest of East Gondwana and to drift northward. Also at about the same time, as a result of the formation of the North Atlantic rift, present-day North America lost its direct connection to South America and Africa, but retained its connection to Europe. In the Upper Jurassic or Lower Cretaceous, present-day South