Geochimica et Cosmochimica Acta, 1956, Vol. 10, pp. 230 to 237. Pergamon Press Ltd., London

Age of meteorites and the earth

CLAIRE PATTERSON
Division of Geological Sciences
California Institute of Technology, Pasadena, California

(*Received* 23 *January* 1956)

Abstract—Within experimental error, meteorites have one age as determined by three independent radiometric methods. The most accurate method (Pb^{207}/Pb^{206}) gives an age of $4{\cdot}55 \pm 0{\cdot}07 \times 10^9$ yr. Using certain assumptions which are apparently justified, one can define the isotopic evolution of lead for any meteoritic body. It is found that earth lead meets the requirements of this definition. It is therefore believed that the age for the earth is the same as for meteorites. This is the time since the earth attained its present mass.

IT seems we now should admit that the age of the earth is known as accurately and with about as much confidence as the concentration of aluminium is known in the Westerly, Rhode Island granite. Good estimates of the earth's age have been known for some time. After the decay-constant of U^{235} and the isotopic compositions of common earth-leads were determined by NIER, initial calculations, such as GERLING'S, roughly defined the situation. Approximately correct calculations were made by HOLMES and by HOUTERMANS on the basis of bold assumptions concerning the genesis of lead ores. Subsequent criticism of these calculations created an air of doubt about anything concerning common leads and obscured the indispensable contributions which these investigators made in establishing the new science of the geochemistry of lead isotopes. When the isotopic composition of lead from an iron meteorite was determined, we were able to show that a much more accurate calculation of the earth's age could be made, but it still was impossible to defend the computation. Now, we know the isotopic compositions of leads from some stone meteorites and we can make an explicit and logical argument for the computation which is valid and persuasive.

The most accurate age of meteorites is determined by first assuming that meteorites represent an array of uranium-lead systems with certain properties, and by then computing the age of this array from the observed lead pattern. The most accurate age of the earth is obtained by demonstrating that the earth's uranium-lead system belongs to the array of meteoritic uranium-lead systems.*

The following assumptions are made concerning meteorites: they were formed at the same time; they existed as isolated and closed systems; they originally contained lead of the same isotopic composition; they contain uranium which has

* C. PATTERSON: N.R.C. Conference on nuclear processes in geologic settings, 1955 September meeting, Pennsylvania State University. Except for minor disagreements, this paper is probably a concrete expression of the attitudes of most investigators in this field, both here and in Europe. The author is grateful to his colleagues, CLAYTON, INGHRAM, TILTON, WASSERBURG, and WETHERILL, for their criticisms which helped clarify this paper.

the same isotopic composition as that in the earth. On the basis of these assumptions various leads might be expected to evolve as a result of different original U/Pb ratios in separate meteorites, and an expression* for any pair of leads derived from such an array is:

$$\frac{R_{1a} - R_{1b}}{R_{2a} - R_{2b}} = \frac{(e^{\lambda_1 T} - 1)}{k(e^{\lambda_2 T} - 1)} \tag{1}$$

where $R_1 = Pb^{207}/Pb^{204}$ and $R_2 = Pb^{206}/Pb^{204}$ for leads from different meteorites a and b, $k = U^{238}/U^{235}$ today (137·8), $\lambda_1 = U^{235}$ decay-constant ($9{\cdot}72 \times 10^{-10}$ yr^{-1}), $\lambda_2 = U^{238}$ decay-constant ($1{\cdot}537 \times 10^{-10}$ yr^{-1}), and T = age of the array.

The isotopic compositions of leads isolated from three stone and two iron meteorites are listed in Table 1 (PATTERSON, 1955). Because the radiogenic and nonradiogenic leads may occur in different mineral environments in a stone meteorite and the sample dissolution procedures may be chemically selective, the lead ratios for the first three meteorites in Table 1 have estimated errors from the absolute of about 2%. The lead ratios for the last two meteorites in Table 1 have estimated errors from the absolute of about 1%.

Table 1. The isotopic compositions of lead in meteorites

Meteorite	Pb Composition		
	206/204	207/204	208/204
Nuevo Laredo, Mexico	50·28	34·86	67·97
Forest City, Iowa	19·27	15·95	39·05
Modoc, Kansas	19·48	15·76	38·21
Henbury, Australia	9·55	10·38	29·54
Canyon Diablo, Arizona	9·46	10·34	29·44

These leads cover an extreme range in isotopic composition and satisfy expression (1), yielding, within experimental error, a unique value of T. This is illustrated in Fig. 1, where it is shown that the Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios from meteorite leads lie on a straight line whose slope corresponds to an age of $4{\cdot}55 \times 10^9$ yr. The dotted lines indicate how stone meteorite leads have evolved. It is clear that the assumptions of the age method are justified by the data. Errors in the lead data and in the decay-constants contribute about equally to the overall error in the calculated age, which amounts to about 1½%. The age for the meteorite array is calculated to be $4{\cdot}55 \pm 0{\cdot}07 \times 10^9$ yr.

The assumptions have not been shown to be unique. The data can be explained

* A similar form of this expression was first used by A. NIER in 1939. F. HOUTERMANS has termed the expression an "isochron." References for the constants are: (k) M. INGHRAM; Vol. 14 Manhattan Project Tech. Sev., Div. 2, Gaseous Diffusion Project, Chap. V, p. 35 (1946); (λ_1, λ_2) E. FLEMING, A. GHIORSO, and B. CUNNINGHAM: *Phys. Rev.* **88**, 642 (1952).

by other qualifying or even contradictory assumptions. Most of these can be excluded as improbable. One common criticism should be mentioned: the time of a process of division or agglomeration of meteoritic material (without differentiation) cannot be distinguished by this age method. It seems probable that any such process of division or agglomeration would be accompanied by chemical differentiation. Any meteorite which had a differentiation history after its initial formation would fall off the isochron. The five meteorites in Table 1 represent a most extreme range of differentiation which occurred during the initial process of

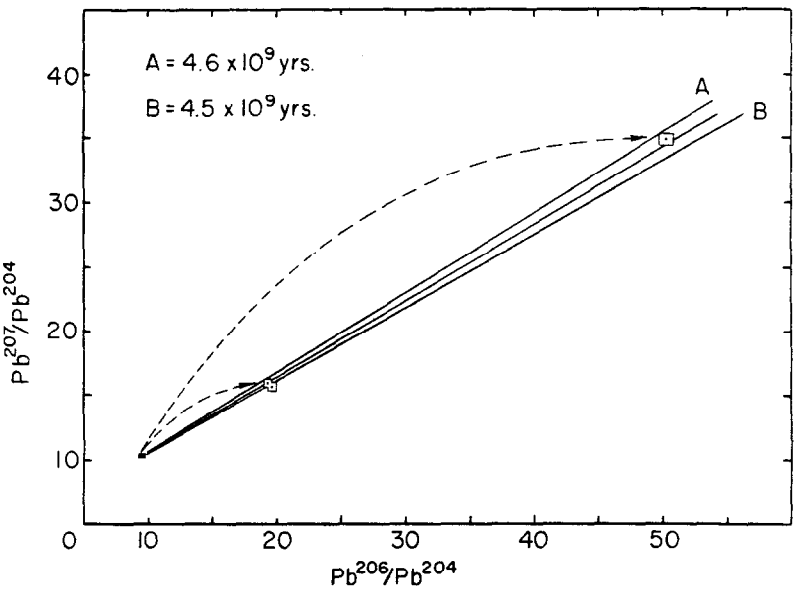

Fig. 1. The lead isochron for meteorites and its estimated limits. The outline around each point indicates measurement error.

formation. This criticism is not serious as far as meteorites are concerned, since if it were valid the lead-lead isochron would date the occurrence of differentiation processes; however, it is important with respect to the age of the earth and will be mentioned later.

At the present time, the next most accurate meteorite age is determined by the A^{40}/K^{40} method. The argon ages of six stone meteorites, three of them determined by WASSERBURG and HAYDEN (1955), and three of them determined by THOMSON and MAYNE (1955), are listed in Table 2. The age of *Forest City* has been redetermined without change by REYNOLDS and LIPSON (1955). Two sets of ages are calculated on the basis of the two reasonable limits of the e^-/β^- branching ratio.

The 0·085 branching ratio is the value obtained by studies of old potassium minerals dated by uranium-lead techniques. The 0·125 branching ratio is the value obtained by counting techniques and by direct measurements of the amounts of decay products. The difference between the two values can be accounted for by systematic loss of radiogenic argon in the old potassium minerals. If one assumes

that a fixed amount of about 20% of radiogenic argon is lost from all stone meteorites, i.e. using a branching ratio of about 0·10, then there is agreement of lead and argon ages for the same stone and an indication that the stones have existed as cold and solid bodies since they were formed. Argon meteorite ages different from the ones mentioned here have been reported by GERLING (1951), and PAVLOVA GERLING and RIK (1954). Since errors in the data presented by GERLING and PAVLOVA cannot be evaluated with any certainty, we cannot be concerned by differences between ages calculated by them and ages calculated from other data. Because of logarithmic behaviour, values for calculated ages of these old samples are insensitive to changes in the e^-/β^- branching ratio. For this reason only disagreements of about 15% between A^{40}/K^{40} and Pb^{207}/Pb^{206} meteoritic ages can be accounted for by a twofold change in the branching ratio. Large age differences must therefore be reconciled on the basis of other experimental errors. Measurements of the amounts of nonradiogenic argon in radiogenic and nonradiogenic argon mixtures are subject to large uncertainties, and for the first four meteorites in

Table 2. A^{40}/K^{40} ages of meteorites

Meteorite	Age $\times 10^{-9}$		Investigators
	($e^-/\beta^- = 0{\cdot}085$)	($e^-/\beta^- = 0{\cdot}125$)	
Beardsley, Kansas	4·8	4·2	WASSERBURG and HAYDEN
Holbrook, Arizona	4·8	4·2	WASSERBURG and HAYDEN
Forest City, Iowa	4·7	4·1	WASSERBURG and HAYDEN REYNOLDS and LIPSON
Akabu, Transjordan	4·4	3·8	THOMSON and MAYNE
Brenham Township, Kansas	4	3	THOMPSON and MAYNE
Monze, Northern Rhodesia	2	2	THOMSON and MAYNE

Table 2, nonradiogenic argon corrections were small. For the last two meteorites in Table 2, nonradiogenic argon corrections were extremely large and the errors in calculated age are excessive. The isotope dilution determination of potassium, used by WASSERBURG and HAYDEN, is nearly an absolute method, while the flame-photometric determination of potassium, used by THOMSON and MAYNE, requires a natural absolute standard which they did not use.

The age of meteorites has been determined by the Sr^{87}/Rb^{87} method. The concentrations of rubidium and strontium and the isotopic compositions of strontium have been determined in two stone meteorites by SCHUMACHER (1955). The Rb/Sr ratio in one stone was so low that any change in isotopic composition of strontium due to radioactivity would be within experimental error. The Rb/Sr ratio in the other stone (Forest City, Iowa) was considerably higher and sufficient

to cause a 10% difference in the relative abundance of Sr^{87} when the isotopic compositions of strontium from both stones were compared.

The value for the decay-constant of Rb^{87} is in question at the present time. Reported values range from 4·3 to 6·7 $\times$ 10^{10} yr for the half-life. Part of the difficulty in the counting techniques of measuring the half-life arises from the fact that the frequency of β^-s at the low end of the energy spectrum increases rapidly with no appearance of a maximum. Measurements of decay products in terrestrial rubidium minerals dated by uranium-lead technique involve errors of open chemical systems. SCHUMACHER'S experiment probably constitutes an ideal case of the geological measurement of the half-life of Rb^{87}, since the ages have been determined by lead methods and the possibility of open chemical systems are remote. His methods of measurement are at least as accurate as the radiometric methods. One would therefore use his data to calculate the half-life of Rb^{87}, using the Pb-Ph isochron age of meteorites. The half-life of Rb^{87}, as determined by these data, is 5·1 $\times$ 10^{10} yr, and is probably the most reliable value at present. The half-life determined by the geological method on terrestrial minerals (5·0 $\times$ 10^{10} yr) agrees well with this.*

Because of the overwhelming abundance of nonradiogenic helium in iron meteorites and the large errors associated with the determination of the concentrations of uranium and thorium in iron and stone meteorites, the age of meteorites by the helium method is not accurate to much better than an order of magnitude (PANETH *et al.*, 1953; DALTON *et al.*, 1953). It has been reported that iron meteorites and the metal phases of stone meteorites were outgassed of helium as of about 5 $\times$ 10^8 yr ago, while the silicate phases of stone meteorites were not (REASBECK and MAYNE, 1955). Such an event would be highly significant and would require detailed evolutionary theory for meteorites. Recent neutron activation (REED and TURKEVICH) and nuclear emulsion (PICCIOTTO) analyses of iron meteorites show that the concentrations of uranium in these bodies are very low, and that the uranium concentrations used for helium age calculations of iron meteorites may be erroneously high. The question is unresolved at present, but it seems reasonable to believe that investigations of meteoritic helium will become vitally important to cosmic-ray studies and may be decisive in meteorite evolution theory, but cannot be used for accurate meteorite-age calculations at the present time.

The Canyon Diablo lead listed in Table 1 was isolated from troilite where the U^{238}/Pb^{204} ratio was shown by direct analysis to be 0·025 (PATTERSON *et al.*, 1953). This ratio is accurate to at least an order of magnitude, and it is so small that no observable change in the isotopic composition of lead could have resulted from radioactive decay after the meteorite was formed. Since stone meteorites were cold and solid during their lifetime, it is unlikely that lead transport could have occurred between iron and stone meteoritic phases if they existed in one body. This iron-meteorite lead is therefore primordial and represents the isotopic composition of primordial lead at the time meteorites were formed. Using the isotopic composition of primordial lead and the age of meteorites, expressions can be

* A value recommended by the work of the geochronology laboratory at the Dept. of Terrestrial Magnetism, Carnegie Institute of Washington.

written for a representative lead which is derived today from any system belonging to the meteoritic array:

$$Pb^{206}/Pb^{204} = 9{\cdot}50 + 1{\cdot}014\ U^{238}/Pb^{204} \tag{2}$$

$$Pb^{207}/Pb^{204} = 10{\cdot}36 + 0{\cdot}601\ U^{238}/Pb^{204} \tag{3}$$

If any two of the three ratios above can be independently measured in the earth's uranium-lead system, and they satisfy expressions (2) and (3), then this system belongs to the meteoritic array and must have its age. Two of the ratios can be measured in a sample of earth lead, but the problem of choosing such a sample is complex because the ratio of uranium to lead varies widely in different rocks and minerals whose ages are short compared to the age of the earth.

One approach is to partition the earth's crust into separate chemical systems of uranium and lead and consider their interactions. Such systems may range from minerals to geochemical cycles. Nearly all of the lead-isotope data concerns either minerals in which the uranium-to-lead ratio is very high (uraninites, etc.) or minerals in which this ratio is essentially zero (galenas). The approximate times of formation of some galenas have been determined, and of these, two dozen or so lately formed galenas may be used as a measure of earth lead (*Nuclear Geology* (1954). W. Faul, Ed.). The isotopic compositions of lead in some recent oceanic sediments have also been determined (PATTERSON, GOLDBERG, and INGHRAM 1953), and these may be used as a measure of earth lead.

Any of these samples will be improper or biased if they are derived from a system of uranium and lead which is only partially closed and is subject to slow but appreciable transport from other systems with different U^{238}/Pb^{204} ratios. In this respect, the sample which may represent the system of largest mass is probably the more reliable. One sample of oceanic sediment lead probably represents more material than a dozen galenas. The isotopic composition of this sediment lead is $Pb^{206}/Pb^{204} = 19{\cdot}0$ and $Pb^{207}/Pb^{204} = 15{\cdot}8$, which satisfies expressions (2) and (3) surprisingly well. It is doubtful if these figures are grossly biased, since a few measurements of uranium and the isotopes of lead in rocks with widely different U^{238}/Pb^{204} ratios indicate rather good mixing to be the first-order effect on the isotopic composition of lead in the earth's crust (PATTERSON, TILTON, and INGHRAM, 1955).

Independent of the absolute abundances of lead isotopes, a rough measure of the rates of change of the lead-isotope abundances in the earth's crust may be obtained from the isotopic composition of galenas of different ages. These rates of change are defined by the ratios of uranium and thorium to lead in the material from which the galenas are derived. From the observed rate of change of Pb^{206}, the U^{238}/Pb^{204} ratio in the earth's crust is found to be 10 (COLLINS, RUSSELL, and FARQUHAR, 1953). This value satisfies expression (2) and (3) for sedimentary lead with unexpectedly good agreement.

In Fig. 2 it is shown that oceanic sediment lead (open circle) falls on the meteoritic lead isochron. Most of the lately formed galenas fall within the dotted outline, although a few are widely aberrant. The position of a lead along the isochron is determined by the U^{238}/Pb^{204} ratio in the system from which the lead

evolves. The arrow indicates the position on the isochron which sediment lead should occupy as predicted by the isotopic evolution of dated ore leads. Independently measured values for all three ratios adequately satisfy expressions (2) and (3), and therefore the time since the earth attained its present mass is $4{\cdot}55 \pm 0{\cdot}07 \times 10^9$ yr.

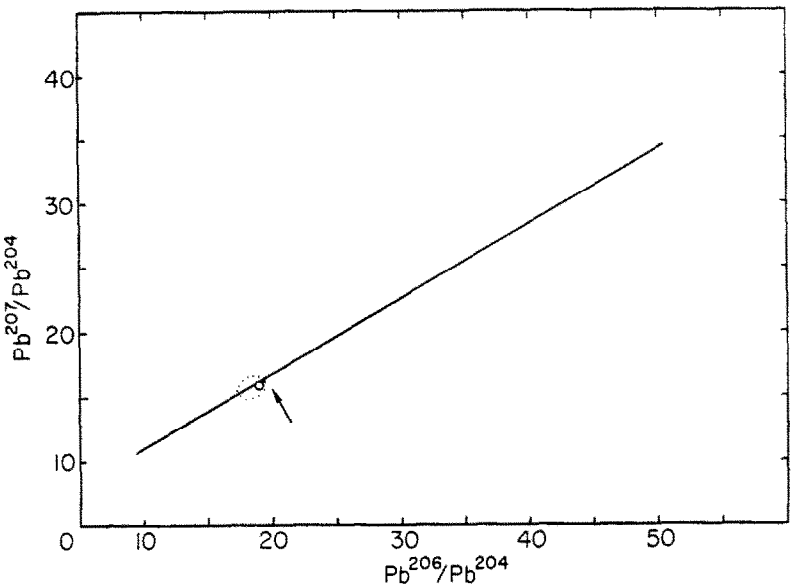

Fig. 2. The relationship between common earth leads and the meteoritic lead isochron.

If the earth is a late agglomeration without differentiation of meteoritic material then it can have any age less than meteoritic material. Rather than arguing that such a process would be accompanied by chemical differentiation (and a change of the U/Pb ratio), it seems reasonable to believe instead that such a late agglomeration process would be less probable than one where both meteorites and the earth were formed at the same time. It is a fact that extreme chemical differentiation occurred during the process which led to the mechanical isolation of the mass of material of which the earth is made, and since changes in this mass were accompanied by chemical differentiation, the Pb/Pb meteorite isochron age properly refers to the time since the earth attained its present mass.

REFERENCES

COLLINS C., RUSSELL, R., and FARQUHAR R. (1953) *Canad. J. Phys.* **31**, 402.
DALTON J., PANETH F., REASBECK P., THOMSON, S., and MAYNE K. (1953). *Nature* **172**, 1168.
GERLING E. and PAVLOVA T. (1951) *Doklady Akad. Nauk, U.S.S.R.* **77**, 85.
GERLING E. and RIK K. (1954) *Meteoritika* **11**, 117.
PANETH F., CHACKETT, K., REASBECK P., WILSON E., DALTON J., GOLDEN J., MARTIN G., MERCER E., and THOMSON S. (1953) *Geochim. et Cosmochim. Acta* **3**, 257.
PATTERSON C., BROWN H., TILTON G., and INGHRAM M. (1953) *Phys. Rev.* **92**, 1234.
PATTERSON C., GOLDBERG E., and INGHRAM M. (1953) *Bull. Geol. Soc. Amer.* **64**, 1387.
PATTERSON C. (1955) *Geochim. et Cosmochim. Acta* **7**, 151.

PATTERSON C., TILTON, G., and INGHRAM M. (1955) *Science* **121,** 69.
PICCIOTTO E. Nuclear Physics Centre, University of Brussells, manuscript.
REYNOLDS J. and LIPSON J. Epipoleological Society, spring 1955 meeting, U.C.L.A.
REASBECK P. and MAYNE K. (1955) *Nature* **176,** 186.
REED G. and TURKEVITCH A. Inst. Nuclear Studies, University of Chicago, manuscript.
SCHUMACHER E. N.R.C. conference on nuclear processes in Geologic Settings (communicated by H. UREY and M. INGHRAM), 1955 Sept. meeting, Penn. State University. (Copies of his manuscript are available).
THOMPSON S. and MAYNE K. (1955) *Geochim et Cosmochim. Acta* **7,** 169
WASSERBURG G. and HAYDEN R. (1955) *Phys. Rev.* **97,** 86.
WASSERBURG G. N.R.C. Conference on nuclear processes in Geologic Settings, 1955 Sept. meeting, Penn. State University.
Nuclear Geology (1954) H. Faul, Ed., J. Wiley, N.Y.