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PRESENT STATUS OF THE LEAD METHOD OF AGE DETERMINATION

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PRESENT STATUS OF THE LEAD METHOD OF AGE DETERMINATION

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Abstract

The available results on the age of radioactive minerals as determined by the various isotopic ratios Pb^{206}/U^{238}, Pb^{207}/U^{235}, Pb^{207}/Pb^{206}, Pb^{206}/Pb^{210} and Pb^{208}/Pb^{232} are summarized. The probable sources of error are each evaluated for the range of conditions expected for these minerals. Nomographs are presented which simplify the calculation of the age of a mineral from the isotopic ratio. It is concluded that the 207/235 and 206/210 ages are the most reliable over the greater range of geologic time. The 206/238 age is generally correct to 5-10% and supersedes the 207/235 age in accuracy for young minerals. The Pb^{208}/Th^{232} age is considered useable for minerals high in thorium content. The 207/206 age is the least reliable of all.

INTRODUCTION

The absolute time scale of geologic history is based primarily on the lead method of age determination. Although the results from this method are supported by a few quantitative rubidium ages on the older rocks and by various semi-quantitative helium ages, nevertheless it is virtually on the lead method alone that we reckon absolute time over 99.9% of earth history. The method includes several independent ways of measuring the time based on the decay of the two isotopes of uranium, U^{235} and U^{238} and the isotope of thorium, Th^{232}, into the stable lead isotopes Pb^{207}, Pb^{206} and Pb^{208} respectively. In addition, by a judicious selection of intermediate members in the decay series from uranium to lead, it is possible to obtain internal checks to prove the absence of contamination, leaching, or leakage phenomena. These secondary age measurements may be thought of as cameras which are continuously recording the behavior of one of the three primary clocks.

Despite the fact that the lead method is the primary basis for geologic time, there are only a few reliable age measurements. Until the classic work of Nier (1, 2) around 1940, the age determinations were all made by the so-called "crude" uranium-lead method which consisted simply of obtaining the ratio of total lead to uranium plus thorium in the mineral. This simple chemical ratio, if properly weighted for the relative activities of the uranium and thorium series, will give reliable ages only if: (1) no common lead was present initially in the mineral, (2) there has been no leaching of uranium or thorium in the history of the mineral, and (3) there has been inappreciable radon loss. Since the chemical data provide no quantitative criteria for any of these three factors, any "crude" age is highly suspect. The third factor can be evaluated by direct measurement and the second factor can be avoided if deep mines are available, but the presence of common lead always remains an imposing uncertainty. From geochemical considerations uraninite from pegmatite should have a very low common lead content but even this criterion is not adequate to provide certainty in the crude age determination. Therefore, although several hundred uranium-lead measurements were reported in the Age of the Earth volume of the National Research Council (3) in 1931 and in subsequent reports of the Committee on Geologic Time (4), it was not until the isotope study of 29 samples by Nier that the modern quantitative era of the lead method began. In the last few years there has been considerable activity in research on this method but to the present time only a few additional complete isotopic analyses have been made (5, 6).

Stieff and Stern (7) have reported a number of isotopic analyses on secondary uranium minerals from the Colorado Plateau area but these apparent ages are complicated by numerous factors. Collins et al. (8) have made isotopic analyses on a number of radiogenic leads from the Canadian Shield area but did not have chemical data on the specimens so that only 207/206 ages were calculated. About two dozen complete isotopic and chemical analyses have been made at this laboratory in recent months. The results will be published elsewhere (9).

The main purpose of this paper is to summarize the past data, to examine the sources of error and to predict for the exploration geophysicist and mining geologist just what may be expected of the lead method.

PRINCIPLES

There are three ways that radiogenic lead may be formed: $U^{238} \longrightarrow Pb^{206}$, $U^{235} \longrightarrow Pb^{207}$, and $Th^{232} \longrightarrow Pb^{208}$. The intermediate products and their respective half-lives are given in Tables 1, 2 and 3. In less than a million years after the deposition of a radioactive mineral the three decay series are essentially in equilibrium and the amount of lead found bears a simple relationship to the age of the mineral. The age is then determined by the ratio of the stable end product lead to any one of the members of the series which is in secular equilibrium. Thus the age may be determined equally well in principle by the ratios Pb^{206}/U^{238}, Pb^{206}/Ra^{226}, or Pb^{206}/Pb^{210}.

Since chemical changes (such as leaching in the late history of a mineral) will affect these ratios in differing degrees, the measurement of several ratios permits quantitative evaluation of the factors which produce erroneous ages. In addition to the ratios of a single series, it is also possible to make use of the ratio Pb^{207}/Pb^{206} since the ratio of U^{235}/U^{238} is geographically constant but the half-lives differ. These clocks involve different chemical characteristics, half-lives and concentrations, so that agreement between them is strong evidence of the reliability of the calculated age.

The equations governing the change in these experimentally measurable ratios with time are straightforward and have been derived by Keevil (10). The final equations modified for the latest constants are given in Table 4. For a comprehensive analysis of many samples it is quite laborious to compute each age, hence simplified nomographs after the manner of Wickman (11) were prepared. Because of their general utility they are reproduced here as Figures 1-4. In these charts the ratios in numbers of atoms are plotted against the age in million years. The charts have been designed for ease in reading and are accurate to 0.1% throughout most of their range.

The problem of determining the concentration of common lead in a radioactive mineral would be hopeless were it not for the presence of Pb^{204} which occurs in all common lead but is not known to be radiogenic. By knowing the ratios of Pb^{204} to Pb^{206}, Pb^{207}, and Pb^{208}

for the common lead of an area in which a radioactive mineral occurs, the amount of common lead of each isotope present in the mineral can be determined.

PUBLISHED RESULTS

The samples for which isotopic and chemical analyses have been published are listed in Table 5. In compiling this table the data was recomputed using the nomographs (Figs. 1-4). The probable errors were estimated from the mass spectrometer data, the uncertainties in the half-lives and isotopic abundance of the uranium isotopes, and the uncertainty in the isotopic composition of the common lead used in making that correction. It does not include possible errors in the U^{235} half-life. Collins' data is not represented since only 207/206 ages are given; neither is that of Stieff and Stern on the carnotite and other secondary minerals of the Colorado plateau.

Possibly the most striking thing about these data is the lack of internal agreement between the various isotopic ages for the same sample. It is clear that additional factors are involved. One observation of particular importance is that the 207/235 ages are generally a little higher than the 206/238 ages while the 207/206 ages are much higher. The explanation for this will be considered later after the errors which affect the age measurements have been discussed.

RADON LEAKAGE

Radon (Rn^{222}) which lies in the U^{238} - Pb^{206} decay chain has a half-life of 3.82 days. Therefore, it may migrate from the site of formation in a radioactive mineral. The radon that escapes will decrease the ultimate 206 content and thus effect the 206/238 and 207/206 ratios. This factor has been the subject of a recent investigation completed at this laboratory (12). It is possible to measure with good reproducibility the radon leakage from uranium-bearing minerals. The results show that samarskites leak to an extent of less than 0.1%, uraninites and pitchblendes leak from 0.1% to 10% and secondary uranium minerals such as carnotite may leak 20% or higher. It has also been found that the leakage rate is temperature dependent as expected for a diffusion process. The leakage is also dependent to a secondary extent on particle size. Since it can be shown theoretically that radon cannot diffuse through a perfect crystal lattice, the leakage is related to the submicroscopic fissures which determine the total effective surface area in the mineral. This is dependent on the amount of ionic substitution as well as the age and the tectonic history of the mineral.

Figure 5 shows the percentage error involved in the 207/206 and 206/238 ages for 1% and 10% radon leakage for minerals of various ages. It is observed that the error in the 206/238 age is directly proportional to the percent radon leakage regardless of the age of the mineral, while the error in the 207/206 age increases exponentially as the age of the mineral decreases.

Experiments have demonstrated that radon leakage is universally present in uranium minerals and is frequently of sufficient magnitude to affect the measured age. Since it is temperature dependent, the integrated radon leakage (over the history of the mineral) is difficult to estimate, so that an appreciable uncertainty from this source remains in the 206/238 and 207/206 ages. It is noteworthy that the 207/235 age is independent of radon leakage. Also the 206/210 age is independent of radon leakage if the rate of leakage has been nearly constant.

LEACHING AND ALTERATION

Recent work by Phair and Levine (13) has shown that leaching affects uranium so much more than lead that it is impossible to lower the age ratio 206/238 by this process. Therefore, recent weathering effects tend to increase the 206/238 and 207/235 ages without appreciably affecting the 207/206 or 206/210 ratios. Figure 6 shows the effect on the two uranium ages for a uranium mineral 1×10^9 years in age for various percentages of uranium leached "yesterday". This is the most likely situation since appreciable leaching occurs only when the mineral reaches the surface of the earth's crust. Figure 7 shows the effect on the 207/206 age of leaching a certain percentage of the uranium out of a mineral of true age 1×10^9 years. The time at which the leaching began is read from the abscissa. Since uranium minerals seldom show evidence of even 5% leaching, this does not seem to be an important factor.

Inasmuch as the Pb^{206}/Pb^{210} ratio is not affected by the leaching of uranium in the relatively recent past and yet is quite precise for young as well as old minerals, the 206/210 ratio is a much more reliable age index than the 207/206 ratio. This Pb^{210} method has been developed recently and applied to a number of classic localities with excellent results. The experimental techniques and theory are described elsewhere (14). A representative comparison of these ages is given as an example in Table 6.

COMMON LEAD

One of the serious problems for the lead method is the correction for common lead. For example, Table 7 shows the effect of common lead correction on the crude age of a mineral. The Wilberforce specimen has negligible common lead and hence gives a reliable "crude" age, while the Caribou Mine specimen would be in error by 700 million years if this correction is ignored.

The isotopic compositions for some common leads reported by Collins (16) are shown in Table 8. The first two were chosen to show the maximum range. This amounts to ±25% of the mean for 206,

±6% for 207 and ±7% for 208. It will be seen from the Broken Hill and Casapalca samples that leads from the same mine or restricted locality have essentially the same isotopic composition regardless of the lead mineral examined.

The sets of samples from the Joplin Lead-Zinc District, the Connecticut pegmatites and the North Carolina pegmatites show that differences in a metallogenic district are not large. The last group in Table 8 gives the average of common lead compositions published by Nier. These averages show a constant trend but individual areas may differ greatly from the average depending on the geochemical history.

The error in the age of a mineral due to the variations in common lead content depends on the concentration of common lead and the choice of the proper composition of that lead.

Figure 8 shows the percentage error found in the age for minerals of various ages with a fixed initial ratio of common lead to uranium of 8 mg. Pb/1 gm. U. The graph shows the effect on the 207/206 and 206/238 ages for the case of (1) no common lead correction-curves A, D, and (2) common lead correction made but with maximum uncertainty in the choice of isotopic composition used in making the correction. The first case applies to all of the pre-1938 uranium-lead ages. The second case applies to any district where no common lead has been analyzed. It is clear that the effect is exponentially greater as the true age of the mineral becomes younger.

The effect of various percentages of common lead on the 207/206 ages is shown in Figure 9. In this graph two cases are illustrated, one for the maximum error in the common lead correction (i. e. complete uncertainty as to the common lead isotopic composition to use) and the other for the error expected if the variation within a district has been defined. This emphasizes the importance of measuring many common leads in the region surrounding an occurrence of uranium mineralization.

The common lead correction is generally based on the non-radiogenic Pb^{204}. However, since the relative abundance of this isotope is subject to the largest error (1% or greater) it is preferable to use the Pb^{208} as a basis for the common lead correction provided that there is negligible thorium present in the mineral.

ERRORS DUE TO OTHER FACTORS

The error in chemical analysis is generally only 0. 1 to 0. 2% for U, Th, and Pb unless the quantity becomes very small. This is the case for Tertiary minerals. However, with special procedures even this small lead content can be determined with sufficient accuracy so that the chemical analysis should never give rise to a significant error.

The mass spectrometer error of 0. 2 to 0. 5% becomes significant only if all other variables are essentially eliminated. If the common lead content remained low the ultimate precision of the lead method would approach 0.5%. Except for the need of some improvement in the precision of measuring the scarce 204, the mass spectrometric technique is not presently a limiting factor in the accuracy of the lead method.

The uncertainty in the half-life of U^{235} is nearly 2% (15). This contributes only 1% error to the 207/235 ratio, but the 207/206 age is much more sensitive to this factor. Figure 10 shows the 207/206 ratio plotted against age. The dashed lines are the equivalent curves for the extremes of the probable error.

GENERAL DISCUSSION

Consider again the question raised by the data of Table 5. It is observed that the 206/238 age is generally a little lower than the 207/235 age but the 207/206 age is considerably higher. This can be explained in various ways: (1) Radon leakage would have the effect of lowering the 206/238 age while raising the 207/206 age to a greater degree. This would make the 207/235 age the most reliable age. (2) If the natural half-life of U^{235} is larger than reported, the age for 207/235 would be high. The 207/206 age would be even higher. (3) Excessive neutron capture by Pb^{206} would produce the observed result.

The third possibility proves to be highly unlikely on perusal of the available data on neutron capture cross-sections.

The fact that virtually all of the 207/206 ages lie to the right of the curve drawn for the "best" half-life suggests that this factor may contribute to the variation in the ages. However since radon leakage would displace the 207/206 ages in the same direction the answer is not obvious. Certainly if the half-life were the major factor, the anomalies would be expected to be quite regular. This is not the case.

It appears that radon leakage is the primary cause of the differences in the ages obtained from the different ratios. The measured leakage at room temperature nearly always brings the ages into better agreement. Since it has been demonstrated that the rate of leakage increases measurably with temperature it is probable that most of the variations can be accounted for in this way, in view of the higher temperatures prevailing at the mineral site over most of its history while at depth.

If this analysis is correct, the most reliable ages will be 207/235 and 206/210, the former because it does not involve radon loss and the latter because it is not affected by recent leaking of the uranium, nor by radon leakage (provided the leakage is essentially constant throughout the history of the mineral). If the present radon leakage can be measured and the integrated leakage estimated, then the 206/238 age is entirely satisfactory, particularly if the leakage is moderately low. For very young specimens there is so little Pb^{207} that the error due to uncertainty in the U^{235} half-life is so great as to render the 207/235 age useless. Further, on very young specimens the uncertainty in the 206/210 ratio due to the difficulty of chemical purification of very small quantities of lead, increases so that in this case the 206/238 ratio coupled with a radon leakage measurement gives the most reliable age.

The 207/206 age is apparently the least reliable. Table 9 lists the 207/206 ages for samples from the same localities measured in different laboratories. The agreement is good, proving that the errors are not in the mass spectrometric determination.

It has been suggested that the 208/232 ages are inferior to the uranium-lead ages. However an analysis of the data of Table 5 as well as unpublished data obtained in this laboratory suggests that in those cases where the uranium and thorium contents of a mineral are both high, the ages are in good agreement. Anomalies do occur for those cases where either uranium or thorium is present in very small amounts.

Finally let us attempt to translate what all this means in terms of practical geological problems.

At the present time there are only a few localities for which the age may be considered as established within 5%. These include Great Bear Lake, 1400; Wilberforce, Ontario, 1070; Parry Sound, 1030; Besner, 780; Katanga, Belgian Congo, 610; Bedford, New York, 350; Middletown, Conn., 260; and Gilpin Co., Colorado, 60 m. y. There are many others which are probably correct to 20% but these are being or will be re-determined shortly along the lines discussed in this paper so that accuracy comparable to these others will be forthcoming.

Equipment is available at a number of laboratories for making the isotopic examination and at least one laboratory has facilities for making the radon leakage measurements. Studies are in progress which may make it possible under some conditions to determine the age of accessory minerals in many types of igneous rocks.

In the immediate future it can be assumed that lead age measurements which approach 1% uncertainty from 50 m. y. to 2,000 m. y. will be attained. This means ±1 m. y. in the Cretaceous; ±2 m. y. in the Permian; ±5 in the Cambrian; and ±20 in the early pre-Cambrian. While this may appear to be phenomenal accuracy in terms of what has been available heretofore, it will be inadequate to study many detailed problems of paragenesis of interest to mining people. It seems unlikely that a metallogenic epoch occurred over many millions of years, and thus its various phases cannot be differentiated at the present time. However it would be wrong to conclude that the ultimate has been achieved.

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TABLE 1

THE URANIUM SERIES

Element	Symbols		Half Life	
Uranium	$_{92}U^{239}$	(UI)	4.51×10^{9}	Years
Thorium	$_{90}Th^{234}$	(Ux_{1})	24.10	Days
Protactinium	$_{91}Pa^{234}$	(Ux_{2})	1.14	Min.
Uranium	$_{92}U^{234}$	(U_{11})	2.50×10^{5}	Years
Ionium	$_{90}Th^{230}$	(Io)	8×10^{4}	Years
Radium	$_{88}Ra^{226}$	(Ra)	1620	Years
Radon	$_{86}Rn^{222}$	(Rn)	3.82	Days
Polonium	$_{84}Po^{218}$	(RaA)	3.05	Min.
Lead	$_{82}Pb^{214}$	(RaB)	26.8	Min.
Bismuth	$_{83}Bi^{214}$	(RaC)	19.7	Min.
Polonium	$_{84}Po^{214}$	(RaC)	164	Microsec.
Thallium	$_{81}Th^{210}$	(RaC)	1.32	Min.
Lead	$_{82}Pb^{210}$	(RaD)	22	Years
Bismuth	$_{83}Bi^{210}$	(RaE)	5.02	Days
Polonium	$_{84}Po^{210}$	(RaF)	138.3	Days
Lead	$_{82}Pb^{206}$	(RaG)	Stable	

TABLE II

THE ACTINIUM SERIES

Element	Symbols		Half Life	
Uranium	${}_{92}U^{235}$	(AcU)	7.13×10^8	Years
Thorium	${}_{90}Th^{231}$	(WY)	25.6	Hours
Protactinium	${}_{91}Pa^{231}$	(Pa)	3.4×10^4	Years
Actinium	${}_{89}Ac^{227}$	(Ac)	22	Years
Thorium	${}_{90}Th^{227}$	(RdAc)	18.6	Hours
Radium	${}_{88}Ra^{223}$	(AcX)	11.2	Days
Radon	${}_{86}Rn^{219}$	(An)	3.92	Sec.
Polonium	${}_{84}Po^{215}$	(AcA)	1.8×10^3	Sec.
Lead	${}_{82}Pb^{211}$	(AcB)	36.1	Min.
Bismuth	${}_{83}Bi^{211}$	(AcC)	2.16	Min.
Polonium	${}_{84}Po^{211}$	(AcC)	.52	Sec.
Thallium	${}_{81}Tl^{207}$	(AcC)	4.76	Min.
Lead	${}_{82}Pb^{207}$	(Pb)	Stable	

TABLE III

THE THORIUM SERIES

Element	Symbols		Half Life	
Thorium	$_{90}Th^{232}$	(Th)	1.39×10^{10}	Years
Radium	$_{88}Ra^{228}$	(Ms Th_1)	6.7	Years
Actinium	$_{89}Ac^{228}$	(Ms Th_2)	6.13	Hours
Thorium	$_{90}Th^{228}$	(Rd Th)	1.90	Years
Radium	$_{88}Ra^{228}$	(ThX)	3.64	Days
Radon	$_{86}Rn^{220}$	(Tn)	54.5	Sec.
Polonium	$_{84}Po^{216}$	(ThA)	.16	Sec.
Lead	$_{82}Pb^{212}$	(ThB)	10.6	Hours
Bismuth	$_{83}Bi^{212}$	(ThC)	60.5	Min.
Polonium	$_{84}Po^{212}$	(ThC)	.3	N. Sec.
Thallium	$_{81}Tl^{208}$	(ThC)	3.1	Min.
Lead	$_{82}Pb^{208}$	(ThD)	Stable	

TABLE IV

Equation and Constants Used in Lead Method

$$\frac{N_{207}}{N_{206}} = \frac{N_{235}}{N_{238}}\left[\frac{e^{\lambda_{235}T}-1}{e^{\lambda_{238}T}-1}\right] = \frac{1}{138}\;\frac{e^{.9722\times10^{-9}T}-1}{e^{.1537\times10^{-9}T}-1}$$

$$\frac{N_{206}}{N_{238}} = 1-e^{-\lambda_{238}T} = 1-e^{-.1537\times10^{-9}T}$$

$$\frac{N_{207}}{N_{235}} = 1-e^{-\lambda_{235}T} = 1-e^{-.9722\times10^{-9}T}$$

$$\frac{N_{208}}{N_{232}} = 1-e^{-\lambda_{232}T} = 1-e^{-.4987\times10^{-10}T}$$

$$T_{1/2}(U^{238}) = 4.51 = .01 \times 10^{9} \text{ yrs.}$$

$$T_{1/2}(U^{235}) = 7.13 = .14 \times 10^{8} \text{ yrs.}$$

$$\frac{N_{238}}{N_{235}} = 138 \pm 1.0\%$$

$$T_{1/2}(Th^{232}) = 1.39 \pm .01 \times 10^{10} \text{ yrs.}$$

TABLE V

Published Lead Isotopic Ages on Radioactive Minerals

		Ages in Million Years			
Sample**	Locality	206/238	207/235	207/206	208/232
N-1	Joachimsthal (Pitchblende)	244±5	249±22	242±200	-
N-2	Katanga, Congo (Pitchblende)	610±4	615±6	626±14	-
N-6	Katanga, Congo (Pitchblende)	567±10	577±16	620±26	-
N-9	Beaver Lodge, N. W. T. (Pitchblende)	337±2	389±2	705±15	-
N-10	Great Bear Lake (Pitchblende)	1220±10	1282±15	1400±20	-
N-11	Bedford, N. Y. (Cyrtolite)	354±4	355±7	385±43	-
N-12	Bedford, N. Y. (Cyrtolite)	329±3	325±8	308±64	-
N-13	Besner, Ont. (Uraninite)	755±4	780±5	826±15	812±1
N-14	Huron Claim, Manitoba (Uraninite)	1555±11	1990±20	2490±3	1090±3
N-28*	Huron Claim, Manitoba (Monazite)	3180±40	2840±15	2610±20	1830±1
N-15	Wilberforce, Ont. (Uraninite)	1057±10	1027±10	1050±20	1000±2
N-17	Morogoro (Uraninite)	790±6	743±6	612±29	-
N-18*	Aust, Agder, Norway (Cleveite)	1070±5	1077±6	1098±20	855±8

TABLE V (Cont'd)

Sample**	Locality	206/238	207/235	207/206	208/232
N-20	Brevig, Norway (Thorite)	-	-	-	238±7
N-19	Pied des Monts, Quebec (Cleveite)	864±5	875±5	890±30	-
N-21	Gullhögen, Sweden (Kolm)	378±12	440±105	800±20	-
N-22	Parry Sound	970±5	1015±10	1050±30	955±20
N-23	Glastonbury, Conn. (Uraninite)	253±3	255±4	293±20	275±4
N-24	Woods Mine, Colo. (Pitchblende)	56±5	60±11	192±300	-
N-25	Gilpin Co., Colo. (Pitchblende)	58±5	64±10	293±350	-
N-26*	Parry Sound (Thucolite)	269±4	282±7	433±20	248±9
N-27	Mount Isa, Australia (Monazite)	-	-	-	933±12
N-29*	Las Vegas, Nev. (Monazite)	1723±40	1547±60	1300±135	770±10
S-GS63	Shinarump No. 1 Claim Grand Co. Utah (Uraninite)	75±5	-	-	-
S-GS64	Happy Jack Mine San Juan Co. Utah (Uraninite)	65±5	-	-	-
K-1	Sunshine Mine, Idaho	710±10	750±10	850±50	-
M-1	Bisundavi, Rajputana, India	733±10	733±15	740±30	-

TABLE V (Cont'd)

Sample**	Locality	206/238	207/235	207/206	208/232
M-2	Soniana, Mewar State, India	660±10	681±20	865±30	

*Low either in uranium or thorium

**N - Nier (1, 2)

S - Stieff and Stern (7)

L - Lamont (9)

K - Kerr and Kulp (5)

M - Nier (6)

TABLE VI

Comparison of 206/238, 207/235, 207/206 With 206/210 Ages for a Selected Set of Samples

Sample No.	Locality	206/238	207/206	207/235	206/210
K-6	Gilpin Co., Colo.	55±2	220±300	58±10	61±3
K-15	Joachimsthal	179±3	425±200	197±15	206±10
K-9	Belgian Congo	574±4	676±25	596±8	650±15
K-19	Nicholson Mine	737±10	1145±30	843±15	808±25
K-18	Eldorado	1015±3	1251±45	1088±14	1105±30

TABLE VII

Effect of Common Lead on "Crude" Pb/U Ages

		Age in million years		
Locality	Pb/U ("Crude")	206/238	207/235	207/206
Wilberforce, Ont.	1060±10 Common lead less than 0.5%	1077±20	1050±20	1035±30
Caribou Mine, Colo.	740±10 (True age about 25 m.y.) Common lead 97%	23±10		

TABLE VIII

Isotopic Abundances of Some Related Specimens of "Common" Lead

		Isotopic abundances referred to Pb Pb^{204}=1.000		
No. *	Locality	206	207	208
C-14	Rosetta Mine, Barberton, South Africa	12.65	14.27	32.78
C-12	Worthington Mine Sudbury, Ontario	26.00	16.94	45.57
C-2	Kengere, Belgian Congo	18.94	15.86	39.70
C-15	Great Bear Lake, N. W. T. Canada	15.93	15.30	35.3
C-16	Ivigtut, Greenland	14.65	14.65	34.48
C-17	Joplin, Missouri	22.35	16.15	41.8
V-23	Joplin, Missouri	22.42	16.01	41.5
V-24	Joplin, Missouri	21.78	15.72	40.8
N-9	Joplin, Missouri	21.65	15.88	40.8
N-10	Joplin, Missouri	21.65	15.74	40.4
N-11	Joplin, Missouri	22.38	16.15	41.6
N-22	Broken Hill, N.S.W.	16.07	15.40	35.5
N-23	Broken Hill, N.S.W.	15.93	15.29	35.3
N-1	Galena, Casapalca Mine, Pa.	18.85	15.66	38.6
N-2	Bournonite, Casapalca Mine, Pa.	18.67	15.45	38.2

TABLE VIII (Cont'd)

No. *	Locality	206	207	208
L-10	Middletown, Conn.	18.81	15.85	39.0
L-11	Darien, Conn.	18.87	15.66	38.6
L-12	Roxbury, Conn.	18.78	15.88	39.0
L-26	Silver Hill Mine, N. C.	18.41	15.85	38.3
N-18	Yancey Co., N. C.	18.43	15.61	38.2
N	Post Paleozoic Av.	18.94	15.69	38.64
N	Paleozoic Av.	17.84	15.53	37.90
N	Pre-Cambrian Av.	15.70	15.16	35.25

*N - Nier (1, 2)
C - Collins (16)
V - Vinogradov (17)
L - Lamont (18)

TABLE IX

207/206 Ages from Different Laboratories on Same Deposits

Sample & Laboratory*	Locality	207/206 Age
N-1	Belgian Congo	632±13
L-9	Belgian Congo	676±25
C-X	Belgian Congo	615 to 655 (5 samples)
N-10	Great Bear Lake	1397±20
L-16	Great Bear Lake	1407±50
C-1	Great Bear Lake	1430±40
C-2	Great Bear Lake	1410±60
C-3	Great Bear Lake	1330±30
C-4	Great Bear Lake	1350±50
L-20	Witwatersrand	1960±40
C-X	Witwatersrand	2070±100
N-15	Wilberforce, Ont.	1035±20
C-68	Wilberforce, Ont.	1090±50
C-69	Wilberforce, Ont.	1032±10
C-70	Wilberforce, Ont.	1025±15

*L - Lamont (18)
N - Nier (1, 2)
C - Collins (16)
C-X - Collins, unpublished results

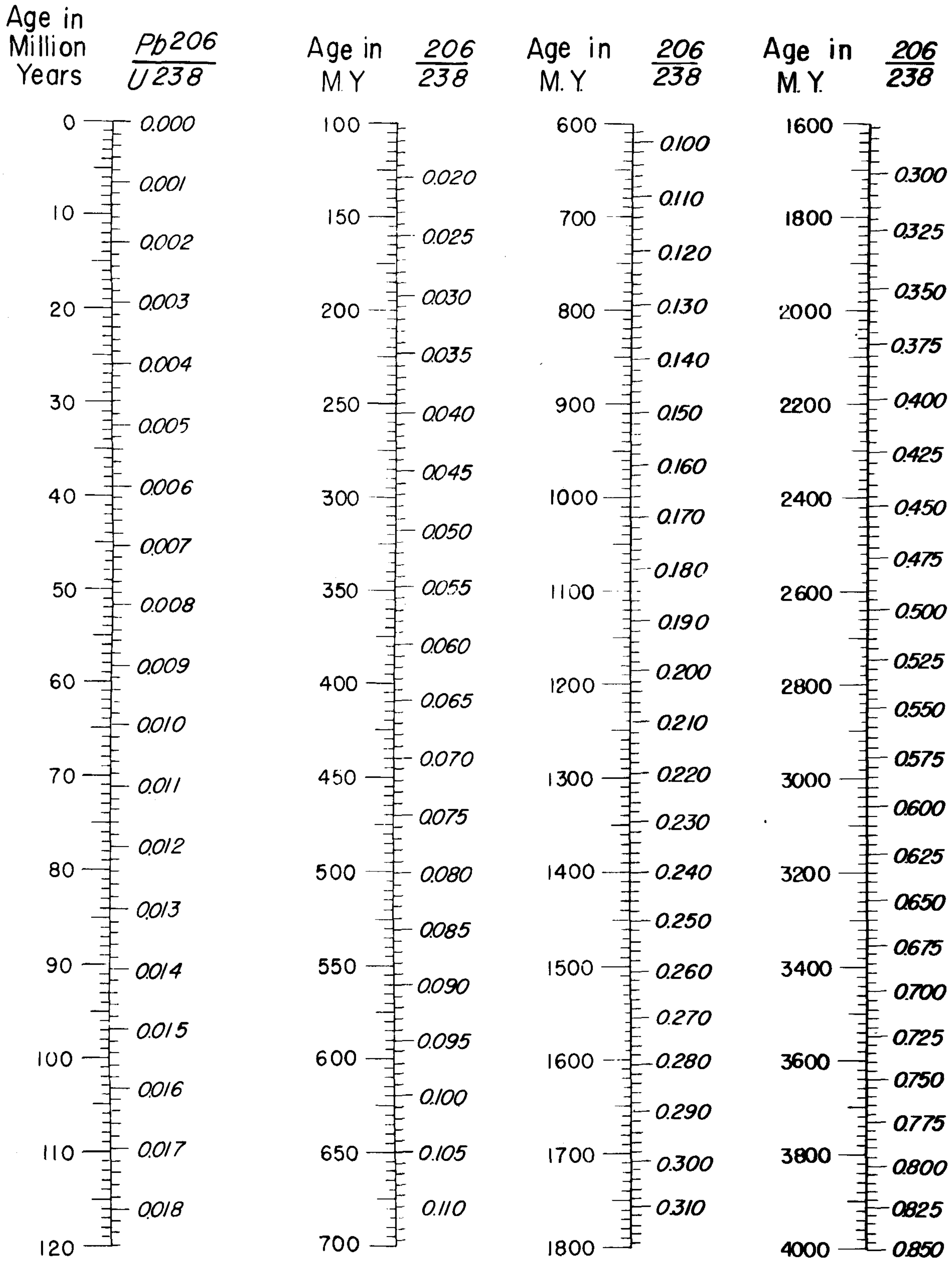

Fig. 1—Nomograph for 206/238 ages

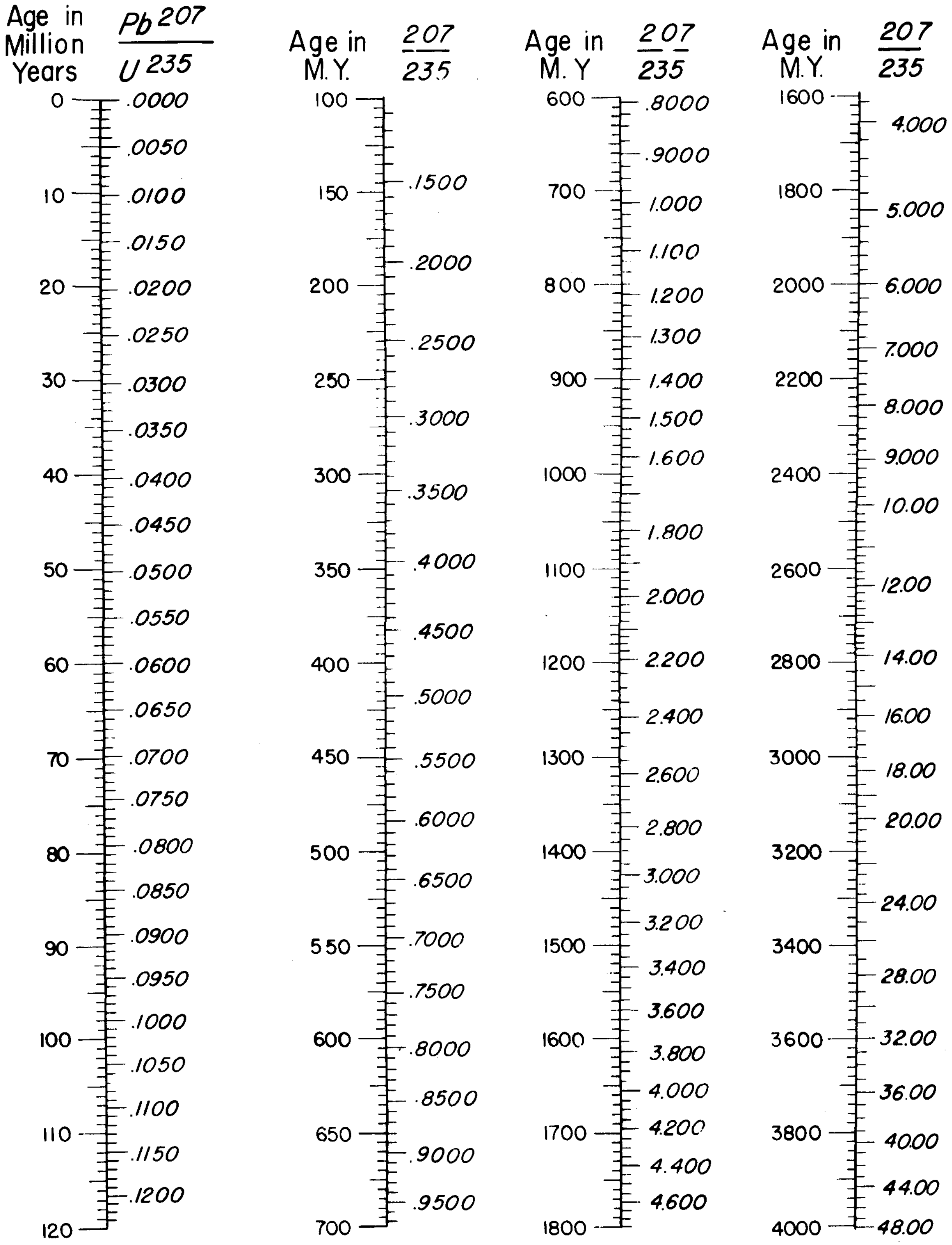

Fig. 2—Nomograph for 207/235 ages.

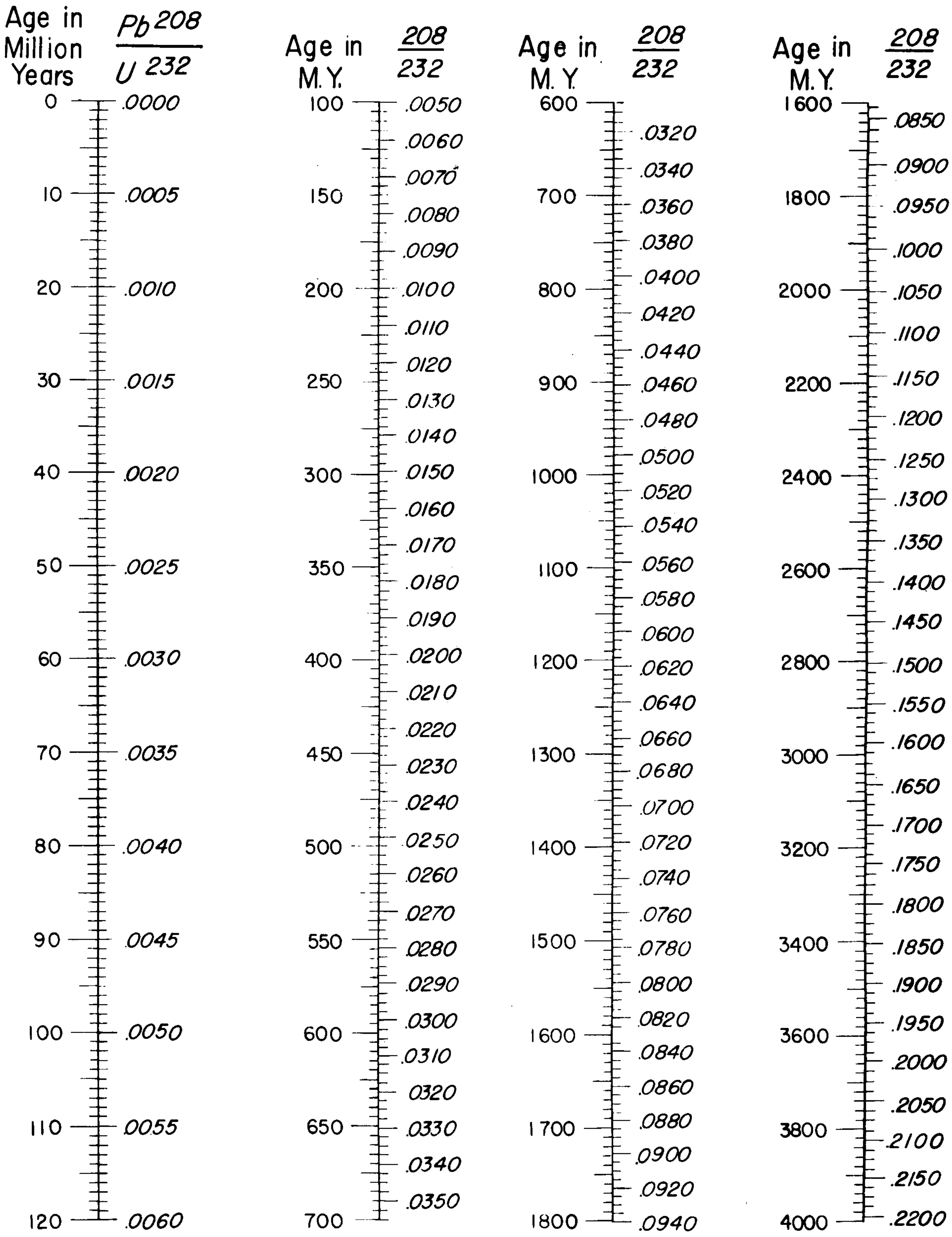

Fig. 3—Nomograph for 208/232 ages.

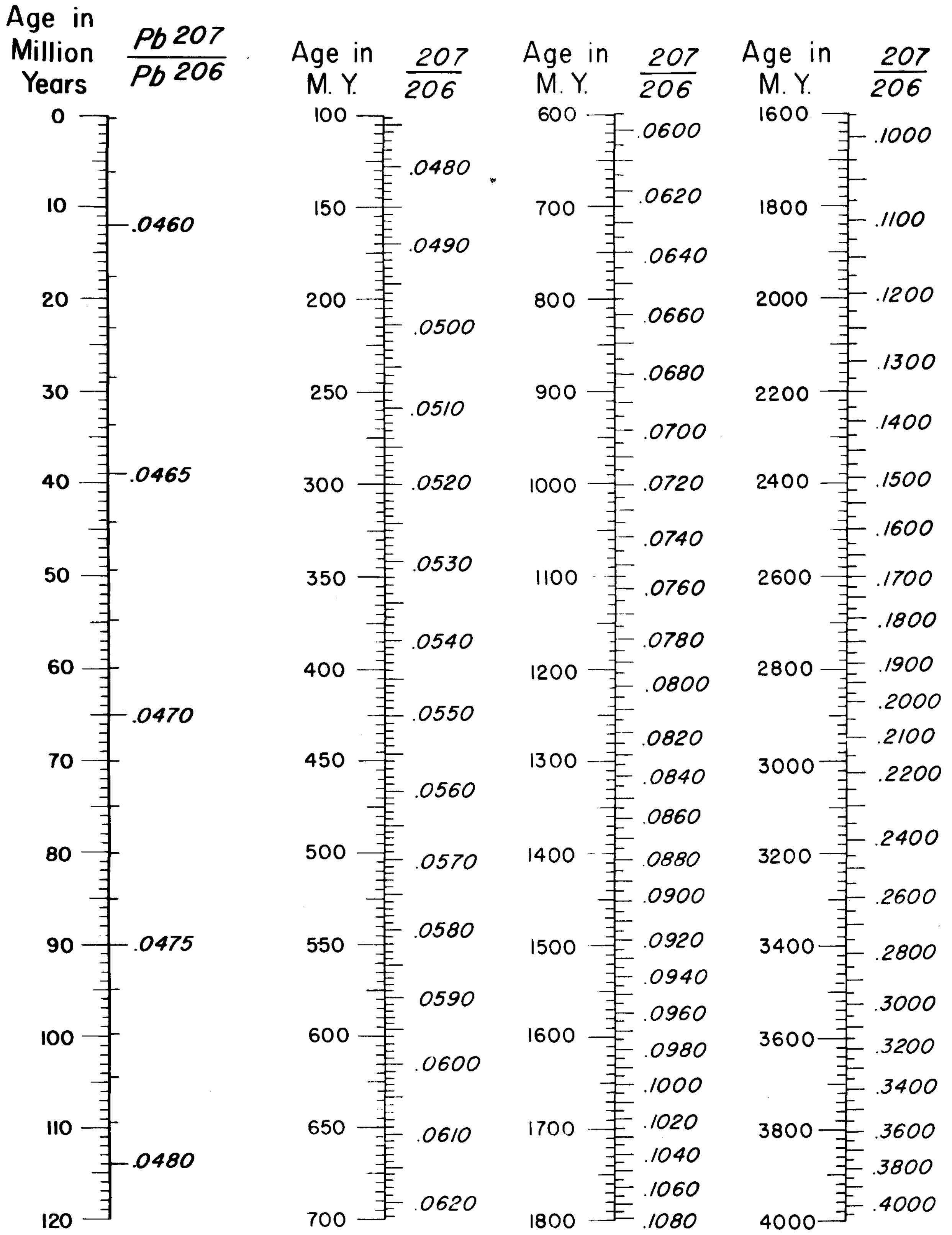

Fig. 4—Nomograph for 207/206 ages.

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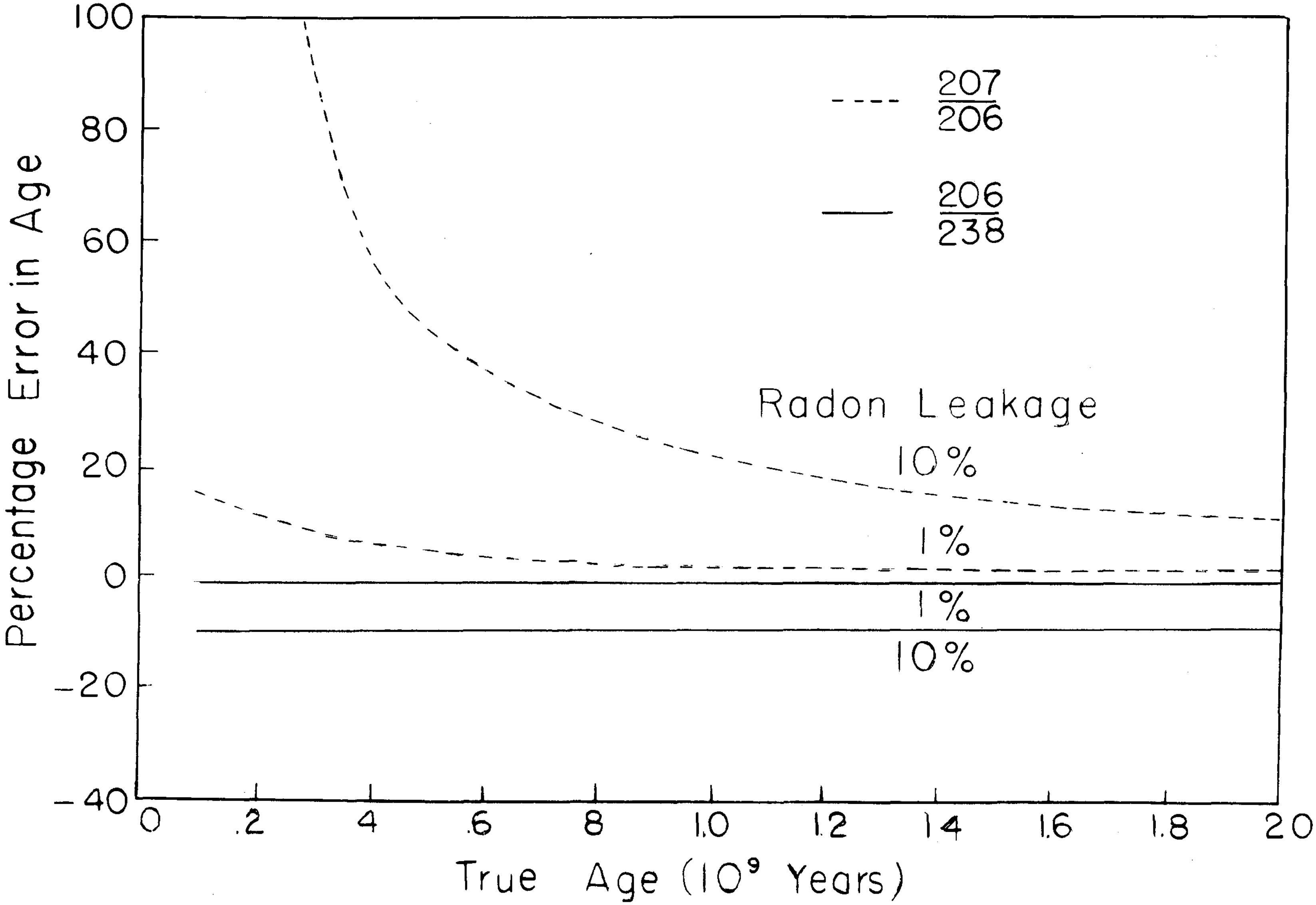

Fig. 5—Percentage error in 207/206 and 206/238 ages for 1% and 10% radon leakage for minerals of various ages.

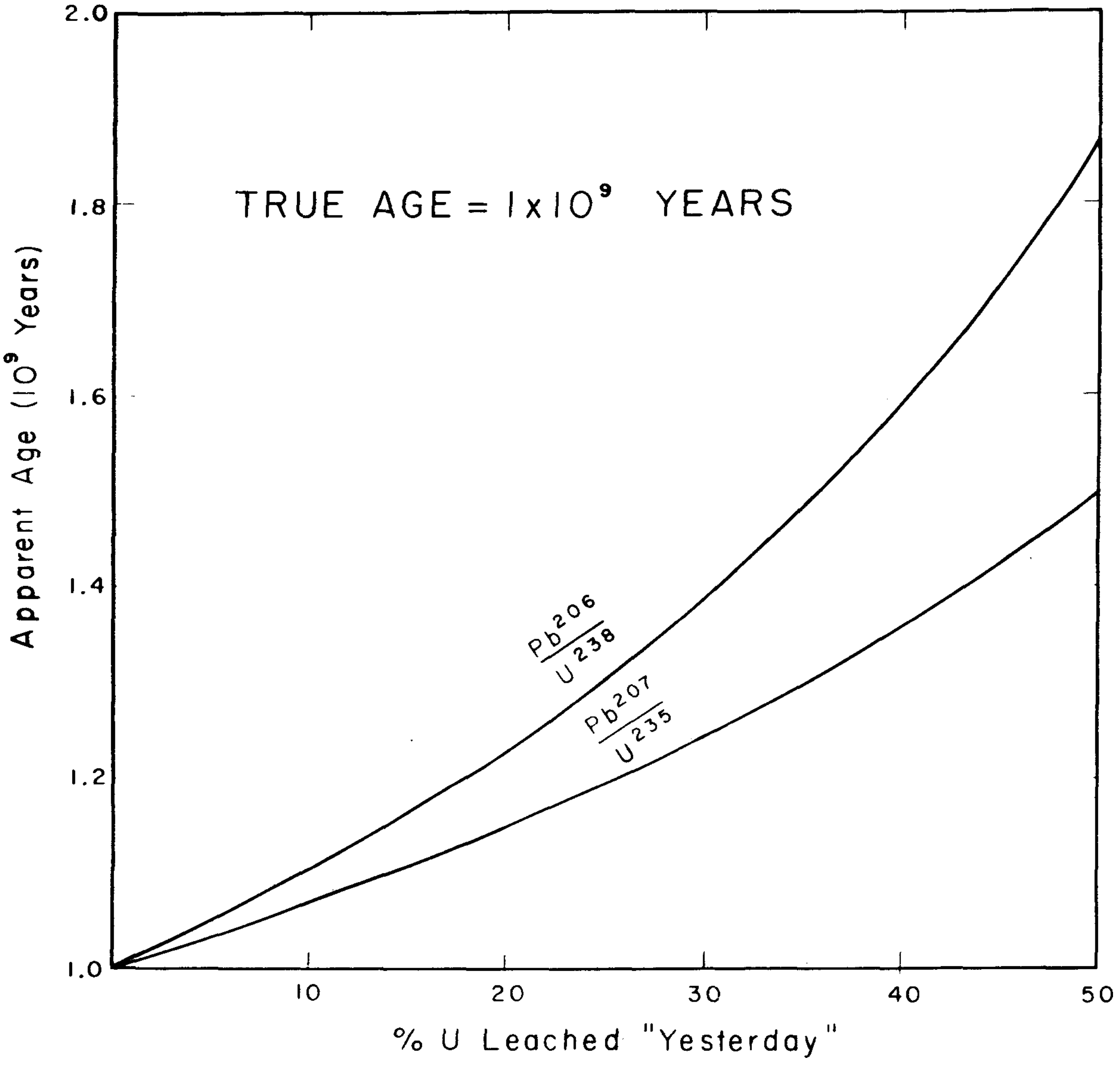

Fig. 6—Apparent 206/238 and 207/235 ages of a mineral whose time age 1 × 10^9 years for various fractions of uranium leached "yesterday".

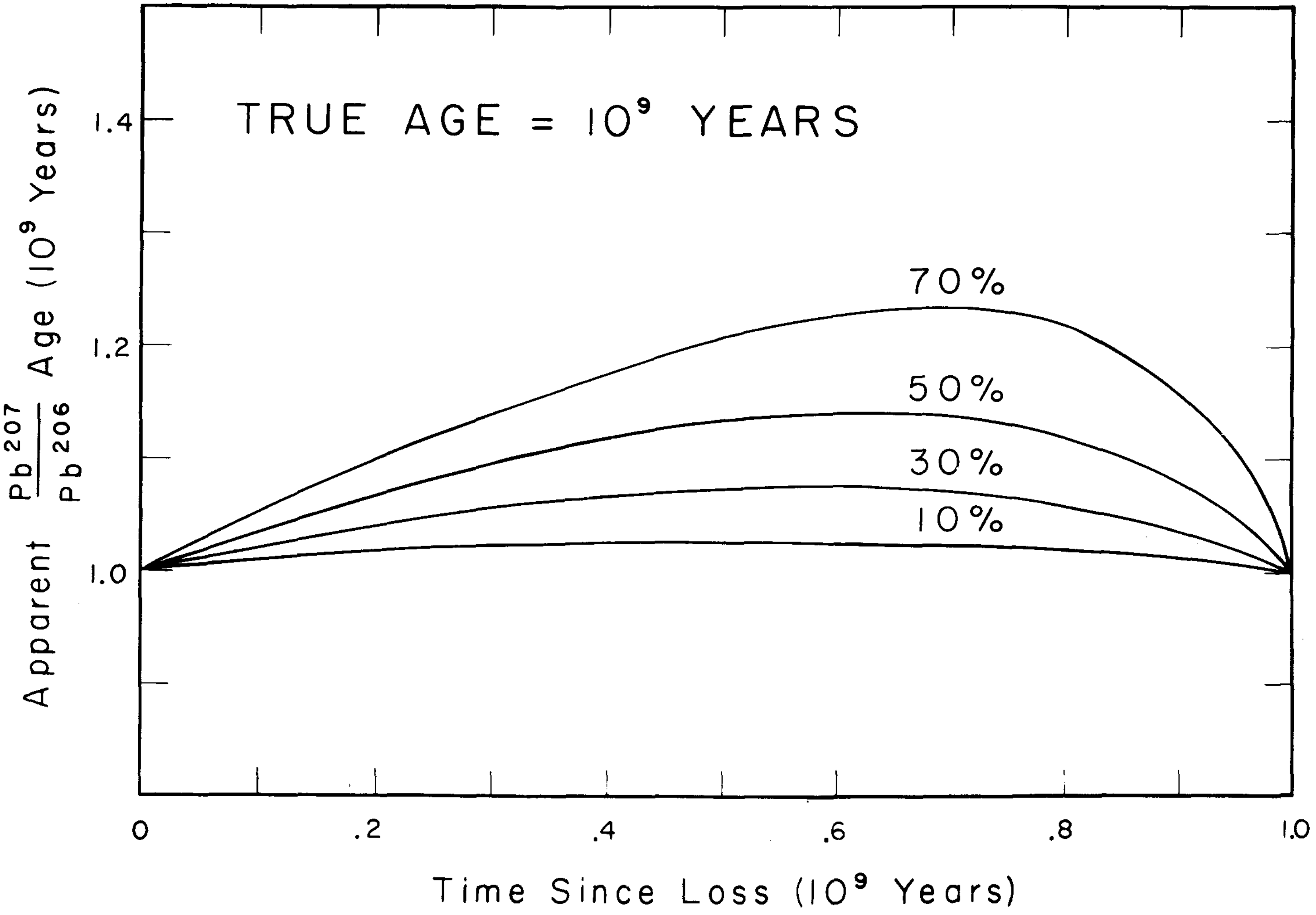

Fig. 7—Error in 207/206 age due to leaching of uranium at a specific time for a mineral 1 × 10^9 years in age.

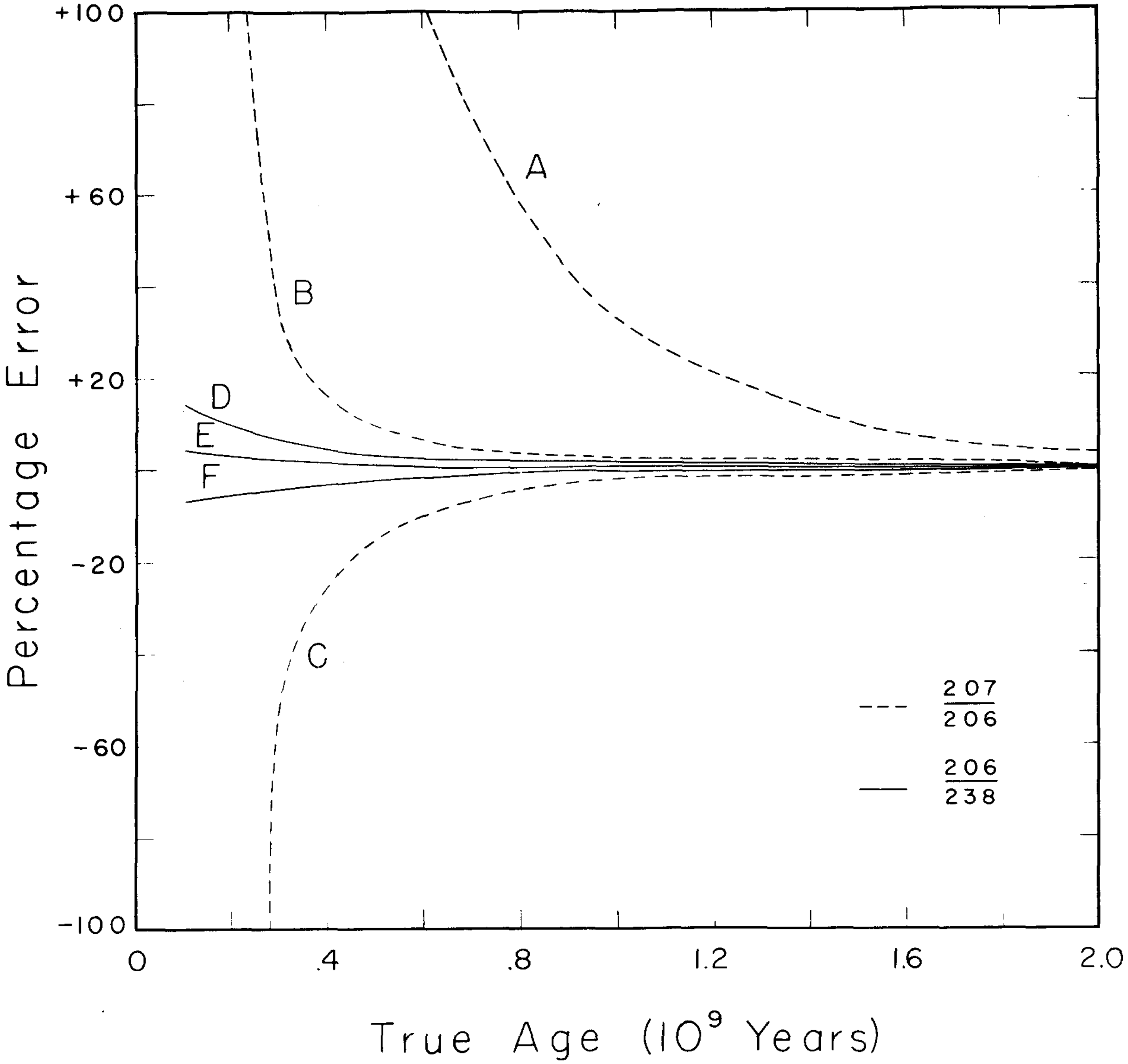

Fig. 8—The effect of common lead on 207/206 and 206/238 ages. A and D no common lead correction. B, C and E, F show case of maximum uncertainty in choice of isotopic composition used in making the correction.

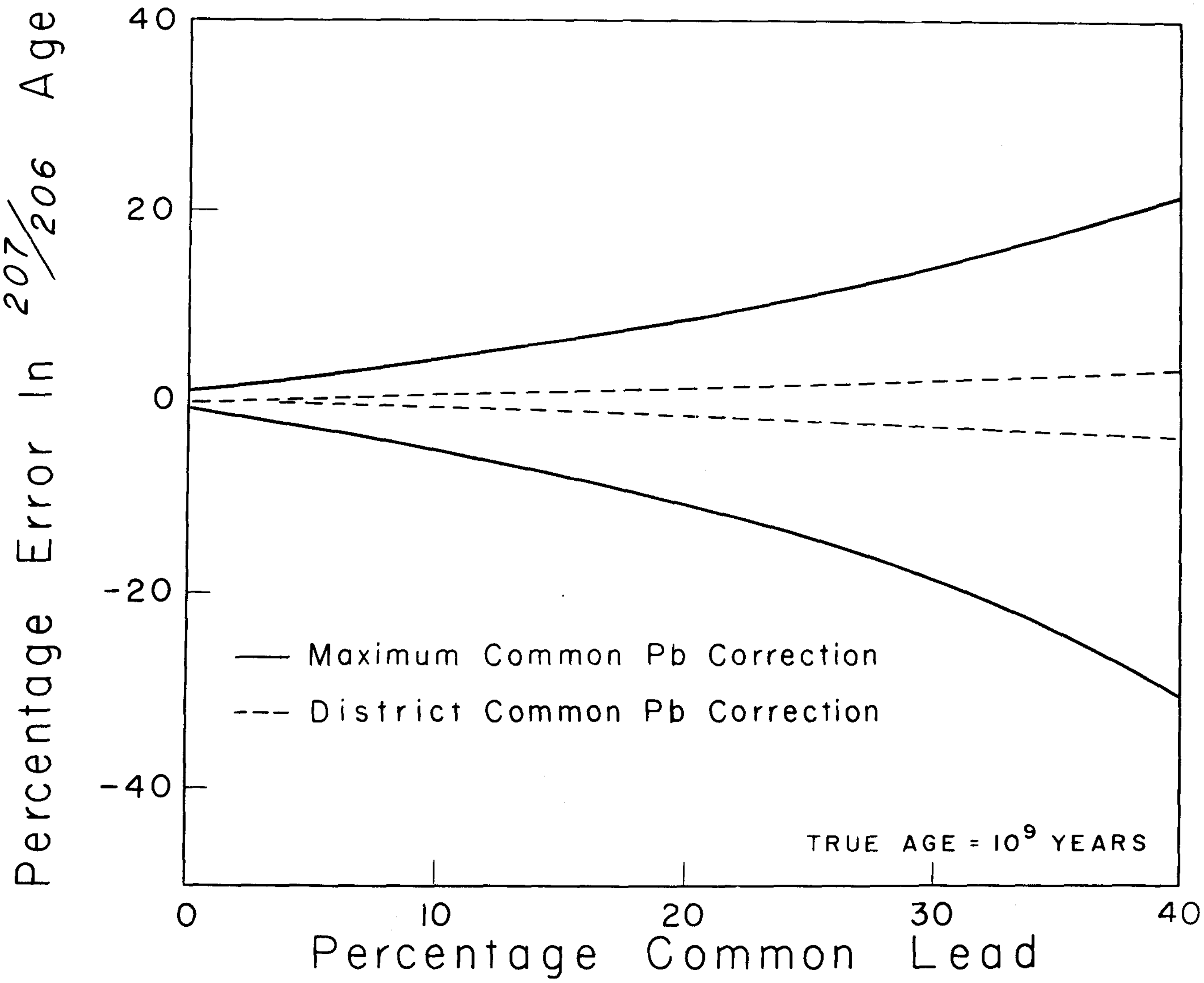

Fig. 9—Effect of various concentrations of common lead on 207/206 ages. Two cases are shown: (1) maximum uncertainty in isotopic composition of common lead used for correction; (2) uncertainty in isotopic composition of common lead limited to range of compositions observed in a district.

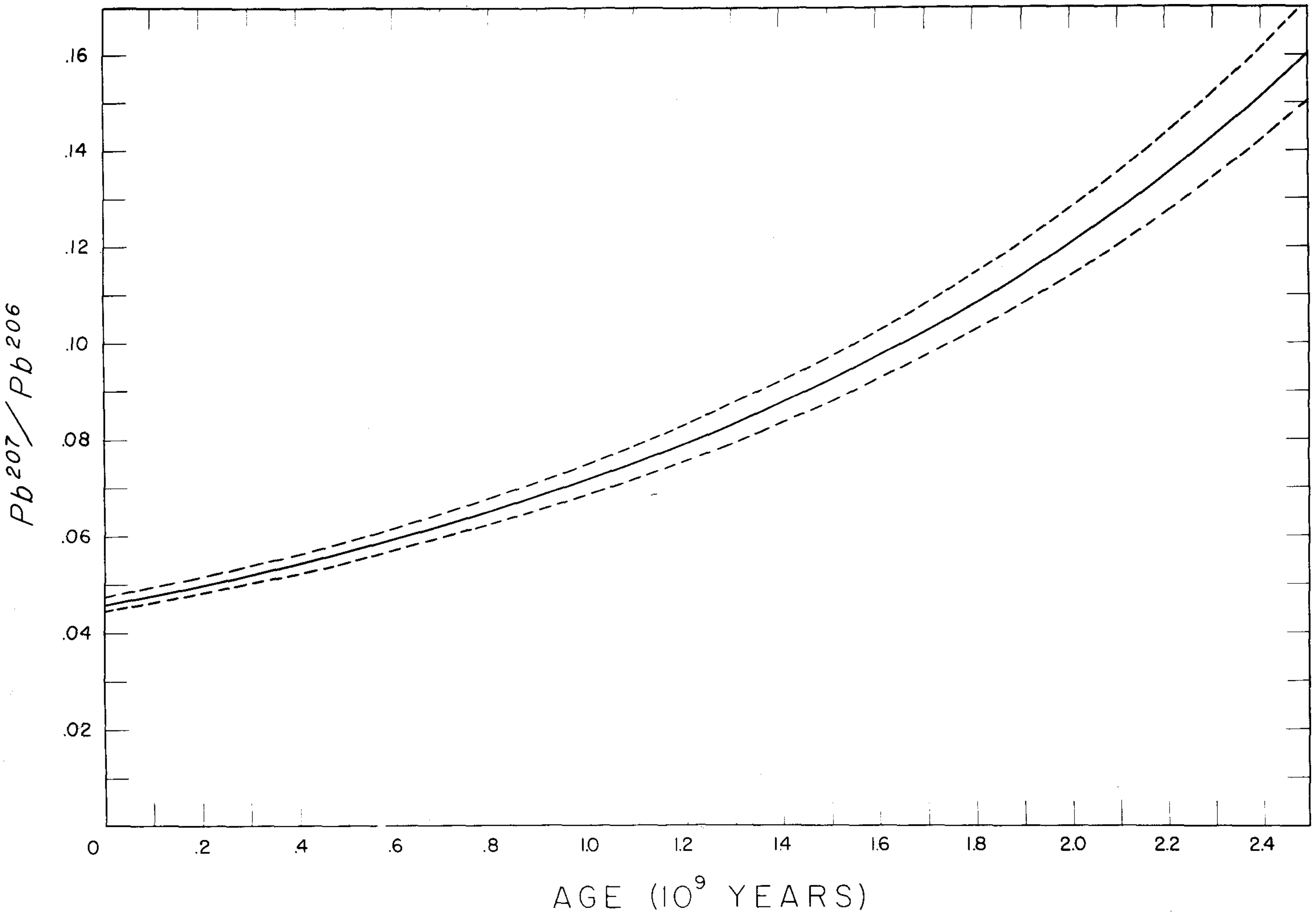

Fig. 10—207/206 ratio as a function of age. Dashed lines indicate the probable error due to uncertainty in the half-life of U^{235} and the relative abundance of the uranium isotopes.

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