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Dr. T. H. Johnson, Director
Division of Research
U. S. Atomic Energy Commission
1901 Constitution Ave., N. W.
Washington 25, D. C.

Dear Dr. Johnson:

Transmitted herewith is one copy of TEI-268, "A preliminary determination of the age of some Colorado Plateau uranium ores by the lead-uranium method," by L. R. Stieff, T. W. Stern, and R. G. Milkey, January 1953. We plan to publish this report as a Circular.

Sincerely yours,

V. E. McKelvey
for W. H. Bradley
Chief Geologist

✓ LWB

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Geology - Mineralogy

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Series A.

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# A PRELIMINARY DETERMINATION OF THE AGE OF SOME COLORADO PLATEAU URANIUM ORES BY THE LEAD-URANIUM METHOD *

By

L. R. Stieff, T. W. Stern, and R. G. Milkey

January 1953

Trace Elements Investigations Report 268

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. <u>It is not for public inspection or quotation</u>.

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* This report concerns work done on behalf of the Divisions of Research and Raw Materials of the U. S. Atomic Energy Commission

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by

L. R. Stieff, T. W. Stern, and R. G. Milkey

## ABSTRACT

A study of the $Pb^{206}/U$ and $Pb^{207}/U^{235}$ ages and the $Pb^{207}/Pb^{206}$ ratios of the Colorado Plateau uranium ores has been undertaken by the Geological Survey on behalf of the U. S. Atomic Energy Commission because of its direct bearing on the origin of these ores. A preliminary treatment of the data for 41 ore samples containing more than 0.1 percent uranium gives a mean $Pb^{206}/U$ age of approximately 71 million years, a mean $Pb^{207}/U^{235}$ age of approximately 82 million years, and a mean $Pb^{207}/Pb^{206}$ ratio equivalent to an age of 425 million years. At least part of the large discrepancy between the mean lead-uranium ages and the much less reliable $Pb^{207}/Pb^{206}$ ages is due to small systematic mass spectrometric errors. The extreme sensitivity of the $Pb^{207}/Pb^{206}$ ratio to small mass spectrometric errors invalidates not only the $Pb^{207}/Pb^{206}$ ages but also the corrections for the presence of old radiogenic lead and the selective loss of radon which must be based on precise determinations of the $Pb^{207}/Pb^{206}$ ratio.

Errors in the chemical analyses for lead and uranium introduce uncertainties in the mean $Pb^{206}/U$ age of approximately ± 3 million years. The small systematic mass spectrometric errors should not increase the mean $Pb^{206}/U$ age by more than 3 million years. Better corrections for common lead and additional corrections for selective loss of uranium and the presence of old radiogenic lead should lower the mean $Pb^{206}/U$ age by approximately 10 million

years. If the entire $Pb^{207}/Pb^{206}$ ratio anomaly is assumed to be due to the selective loss of radon, an improbable assumption, the mean $Pb^{206}/U$ age would increase approximately 10 million years.

Our data suggest that the calculated ages are close to the true age of the ores. From these calculated ages it is reasonable to assume that the uranium was introduced into the sediments not later than the end of the Cretaceous or the beginning of the Tertiary (55 to 75 million years ago). This assumption differs markedly from the assumption that the present uranium deposits were formed in the late Triassic and late Jurassic sediments of the Colorado Plateau (152 and 127 million years ago, respectively) during or soon after deposition of the sediments. Careful study is continuing in order to reduce the uncertainties in interpretation of both field and laboratory data so that a satisfactory hypothesis of origin of these ores may be securely established. To place this laboratory study on a firmer basis, ages are being determined by the lead-uranium methods on many additional carefully selected samples of uraninite and other primary ore minerals.

## INTRODUCTION

The immediate objective of the present study of the age of the Colorado Plateau uranium ores by the lead-uranium methods has been to determine whether the uranium deposits in the Shinarump conglomerate are late Triassic (152 million years) and those in the Morrison formation late Jurassic (127 million years) in age, (Holmes, 1946a, p. 145) as some of the field evidence suggests, or whether all of the deposits are late Cretaceous to early Tertiary (55 to 75 million years in age) as the available lead-uranium age determinations indicate. No attempt has been made to set more precise age limits on the carnotite ores because of the uncertainties that accompany age determinations made on minerals that are probably secondary in occurrence. The uraninite specimens that have been found in some of the Triassic and Jurassic sediments, however, are not as susceptible as carnotite specimens to solution by ground waters, and the ages that have been determined for these uraninites are considered to be more reliable.

This study of the age of the Colorado Plateau uranium ores was begun in 1950 by the Geological Survey on behalf of the U. S. Atomic Energy Commission. The writers believe that the determination of the age of the Plateau ores is one of the most promising lines of investigation directly related to the origin of the ore deposits in the Plateau sediments. The Tertiary ages of Colorado Plateau ores published in works by Hess and Foshag (1927, p. 4), and Holmes (1931, p. 351), and our own preliminary work (Stieff, Girhard, and Stern, 1950, p. 40; Stieff and Stern, 1952, p. 707) did not agree with the ages implied by the widely accepted theory that the ore was deposited shortly after the enclosing Triassic and Jurassic sediments were laid down (Hess, 1914, p. 687; Webber, 1947; and Fischer, 1950, p. 3).

If even an approximate dating of the deposits can be made by laboratory methods, the approach to the problems of the source and the chemical and physical controls of the mineralizing solutions will be simplified. The clarification of these questions on the origin of the deposits has not only considerable scientific interest but also will lead to two immediate practical applications: (1) greater confidence can be placed in the estimates of the ultimate reserves of uranium ore on the Colorado Plateau and in the selection of new areas for exploratory drilling; (2) more thorough evaluation can be made of the prospecting methods and geologic controls used to guide the drilling.

We would like to acknowledge our indebtedness not only to the many members of the Survey who have helped us but also to the Atomic Energy Commission's Division of Research and Division of Raw Materials for the support we have received. Without the isotopic analyses furnished by Dr. Roger F. Hibbs and his staff at the Mass Assay Laboratory, Carbide and Carbon Chemicals Company, Oak Ridge, Tenn., this work would not have been possible. The mill-pulp samples used in this study were obtained through the courtesy of the United States Vanadium Corporation.

## SAMPLES

The sampling of the uranium deposits of the Colorado Plateau for age studies is a specialized problem. This problem requires not only that the ore specimens from each of the deposits in the different mineralized stratigraphic units must be representative but also the specimens must be essentially unaltered if the lead-uranium ages of the specimens are not to be much greater than the actual age of the ore. Obviously, the oxidized and altered, near-surface ores now available on the Plateau offer few opportunities to meet both these requirements. The compromises that have had to be made in fulfilling these conditions, however, have not been considered in the arithmetic averages that have been calculated for this preliminary report. It is realized that these averages are probably greater than the true age of the ore.

The geographic and stratigraphic distribution of all but 2 of the 17 deposits included in this study are shown in figure 1. The deposits not plotted are the Rifle district, Garfield County, Colo., and the Temple Mountain district, Emery County, Utah. A list of the sample localities arranged

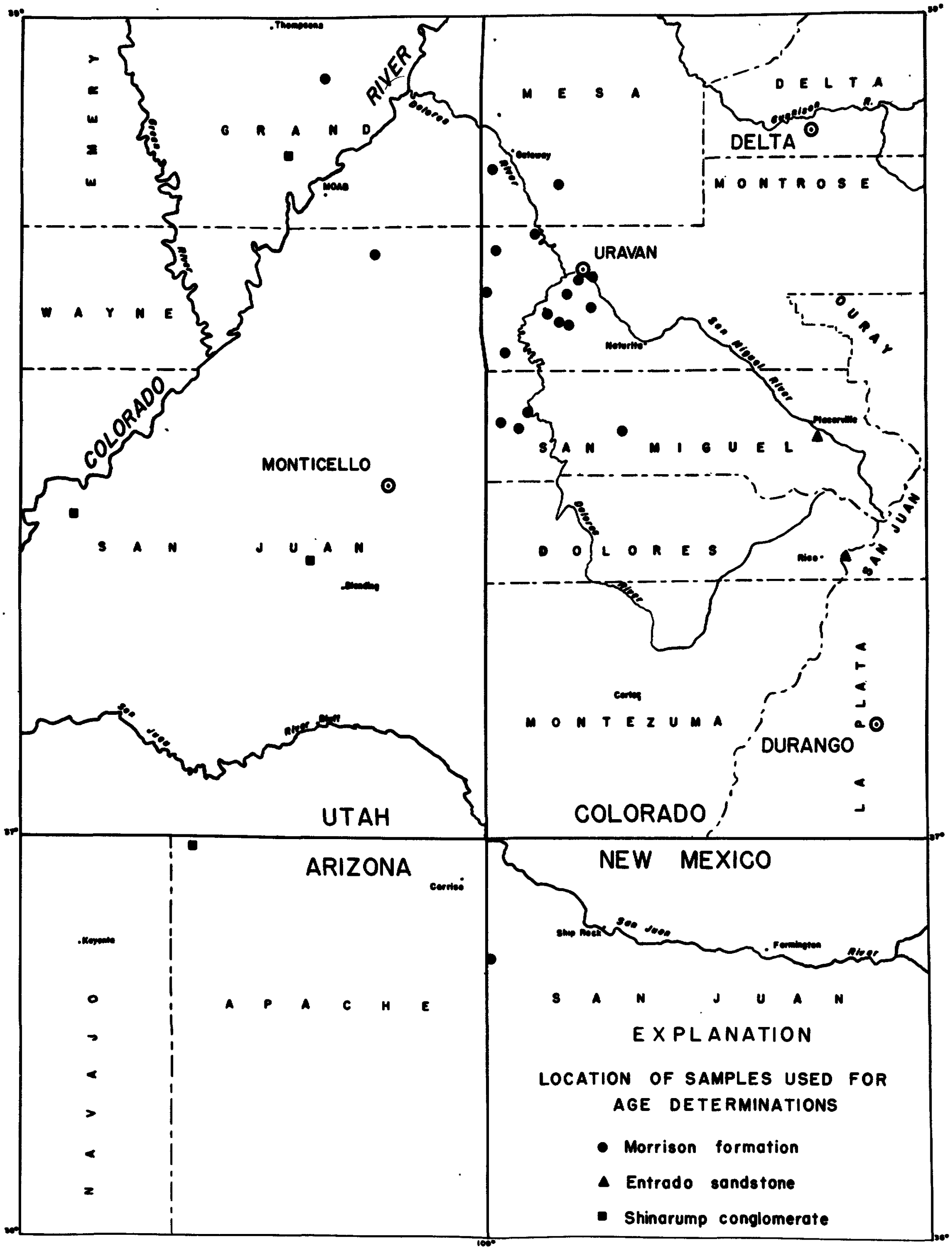

FIGURE 1. — INDEX MAP OF PART OF THE COLORADO PLATEAU

according to the stratigraphic units in which the deposits occur, together with the type of sample, principle uranium-bearing minerals contained, and their $Pb^{206}/U$ ages and their $Pb^{207}/Pb^{206}$ ratios corrected only for common lead is in Appendix 1.

In collecting samples for this age study, an effort was made to obtain as many different types of uranium ore as possible. The uraninite specimens were collected from the Happy Jack mine, San Juan County, Utah, and the Shinarump No. 1 claim, Seven Mile Canyon, Grand County, Utah, both in the Shinarump conglomerate of Triassic age. The oldest Jurassic ores were of the vanadiferous hydromica type (roscoelite) collected from the Entrada sandstone in the vicinity of Placerville, San Miguel County, Colo. Also, a new uranium mineral (coffinite) now being described from the La Sal No. 2 mine, Mesa County, Colo., and an asphaltic ore containing uraninite from the Temple Mountain area, Emery County, Utah, have been collected and analyzed. The remaining samples are typical of the disseminated type of carnotite ores and all except one (from the Monument No. 2 mine, Apache County, Ariz., in the Shinarump conglomerate) have been collected from deposits in the Salt Wash sandstone member of the Morrison formation of Jurassic age. Nine mill-pulp samples representing a total of approximately 4,200 tons of carnotite ore from 7 different mines in the Uravan mineral belt have also been studied.

## PHYSICAL CONSTANTS AND FORMULAS

The physical constants and equations used in the age calculations on the Plateau ores are shown in table 1.

## Table 1.--Radioactive decay schemes, physical constants, and age formulas

### Decay schemes 1/

$$U^{238} \longrightarrow Pb^{206} + 8\ He^{4} \qquad Th^{232} \longrightarrow Pb^{208} + 6\ He^{4} \qquad U^{235} \longrightarrow Pb^{207} + 7\ He^{4}$$

### Physical constants

| | g/gU | Half-life |
|---|---|---|
| $U^{238}$ | 0.99286 | $4.56 \times 10^{9}$ years |
| $Em^{222}$ (Radon) | $2.14 \times 10^{-12}$ | 3.82 days |
| $U^{235}$ | 0.00714 | $7.14 \times 10^{8}$ years |
| $Em^{219}$ (Actinon) | $1.62 \times 10^{-16}$ | 3.92 seconds |

### Equations for the calculation of geologic age 2/

$$t = 1.515 \times 10^{4} \ \log_{10} \left(1 + 1.156 \frac{Pb^{206}}{U^{238}}\right) \quad [t \text{ is in million years}]$$

$$t = 2.37 \times 10^{3} \ \log_{10} \left(1 + 1.14 \frac{Pb^{207}}{U^{235}}\right) \quad [t \text{ is in million years}]$$

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{139.0} \frac{\left(e^{\lambda 235 \ t} - 1\right)}{\left(e^{\lambda 238 \ t} - 1\right)} \quad [t \text{ is in million years}]$$

---

1/ $Pb^{204}$ is not known to be produced by any natural radioactive decay series.

2/ Keevil, N. B., 1939, The calculation of geological age: Am. Jour. Sci., 5th ser., vol. 237, pp. 199, 214.

These constants are the same as those used by Wickman (1939, p. 5) in the preparation of his nomographs for the calculation of geologic age. These nomographs were used in the calculation of some of the ages given in this paper. The most recent redetermination of the half life of $U^{235}$ by Fleming, Ghiorso, and Cunningham (1951, p. 967) does not differ significantly from the value proposed by Nier (1939a, p. 153) which Wickman used.

In this report $Pb^{206}/U$ ages instead of $Pb^{206}/U^{238}$ ages have been calculated because the correction of total U to $U^{238}$ is much less than the chemical errors in the determination for uranium. The isotopic abundance of $U^{238}$ for samples from many different sources has been shown not to differ significantly from the value 99.286% (table 1).

## AGE CALCULATIONS

### Corrections

The calculation of the age of the Plateau uranium ores is subject to corrections for the following:

1. Analytical errors
2. The presence of common lead in the ore
3. The presence of old radiogenic lead in the ore
4. The selective loss of certain radioactive daughter products such as radon
5. The loss of uranium and lead due to alteration of the ore by ground waters

### Analytical errors

Prior to analysis all samples were carefully ground and thoroughly mixed. Samples containing more than 0.1 percent uranium were analyzed volumetrically. All samples were analyzed for lead colorimetrically

(Milkey, 1952, pp. 9-13) after extraction of the lead with dithizone. The results of duplicate volumetric analyses for uranium and colorimetric analyses for lead are usually reproducible to within 2 to 3 percent.

For a sample whose $Pb^{206}/U$ age is 65 million years these analytical chemical errors for the uranium and lead result in a maximum uncertainty of ± 3 million years. A list of the results of the quantitative analyses of the samples used for age determinations is given in Appendix 2.

The limits of precision for the lead isotope analyses are calculated so that 95 percent of any new determinations will fall within the limits given. Systematic mass spectrometric errors are believed to introduce uncertainties in accuracy of less than 1 percent in the reported isotopic analyses. The isotopic analyses of the lead (as the iodide) extracted from the ore are in Appendix 3.

The $Pb^{204}/Pb^{208}$ ratio of many of the radiogenic leads, however, shows considerably greater variation than would be expected from the reported precision and accuracy (fig. 2). The direction of the variation is toward impossibly large amounts of $Pb^{204}$ relative to the $Pb^{208}$ in the samples as the percent abundance of $Pb^{206}$ increases. This type of impossibly high $Pb^{204}/Pb^{208}$ ratio clearly indicates the presence of small systematic mass spectrometric errors.

The systematic error in the $Pb^{204}/Pb^{208}$ ratios of the radiogenic leads is believed to be due partly to the inability of available mass spectrometers to resolve completely the smaller $Pb^{204}$ and $Pb^{208}$ spectrometer peaks from the much larger $Pb^{206}$ peaks of these radiogenic leads. Similar but smaller percentage errors should be expected in the determination of $Pb^{206}/Pb^{207}$ ratios of the radiogenic leads. These errors result in abundances of $Pb^{204}$,

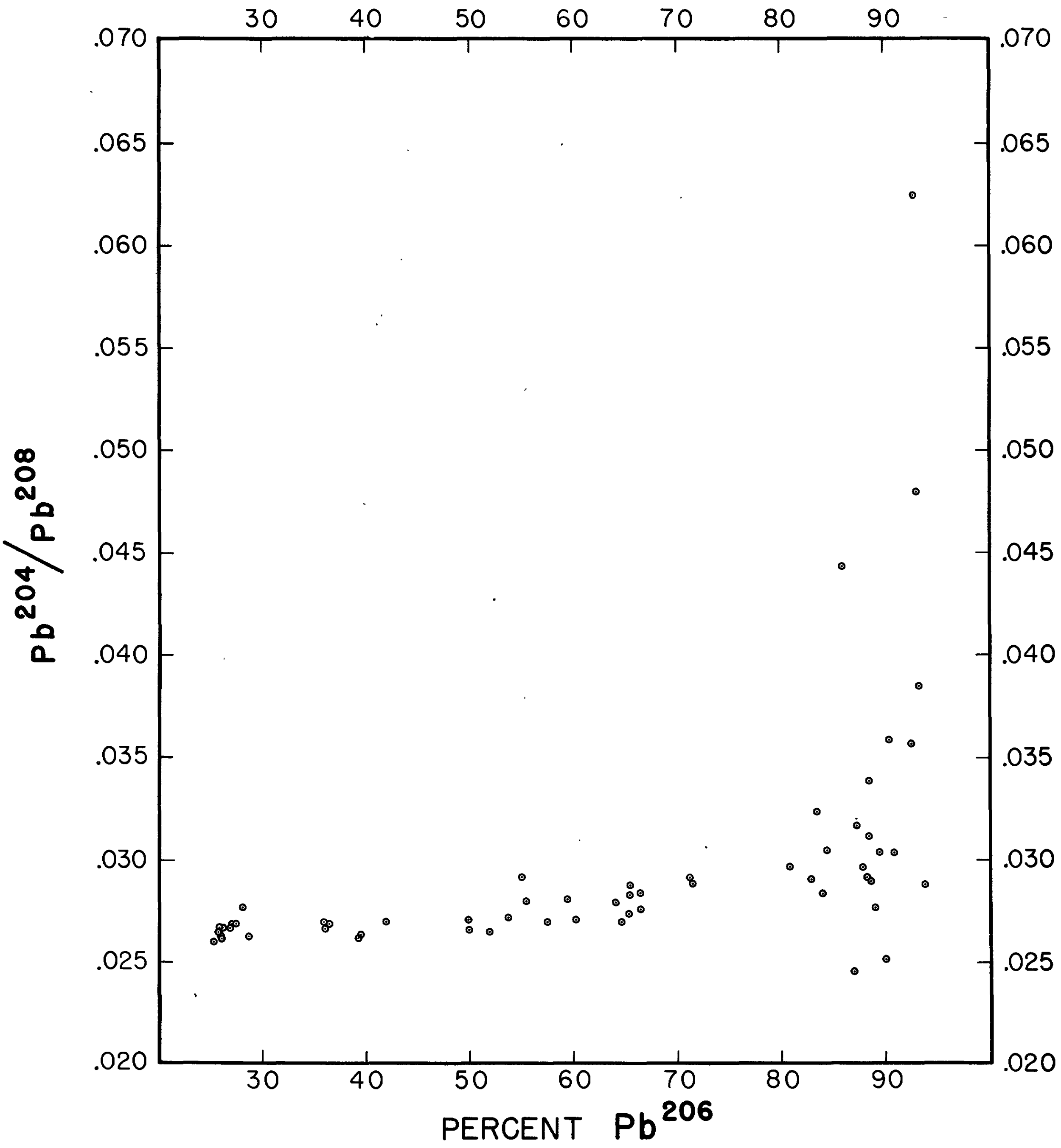

Figure 2.—The effect of increased $Pb^{206}$ on $Pb^{204}/Pb^{208}$

$Pb^{207}$, and $Pb^{208}$ slightly higher than their true values, abundances of $Pb^{206}$ correspondingly lower, and an increase in the mean $Pb^{206}/U$ age of not more than approximately 3 million years.

The isotopic data on the Colorado Plateau leads (fig. 3) are plotted on the $Pb^{206}$, $Pb^{207}$, $Pb^{208}$ plane of a tetrahedron which has $Pb^{204}$, $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ at its corners. The sum of the isotopic abundances of $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ plotted in this way is 100 percent and $Pb^{204}$ does not appear. $Pb^{204}$ has been deliberately omitted from figure 3 because of the large uncertainty involved in determining its abundance. Figure 3 shows, as does figure 2, the increasing effect of the small mass spectrometric errors as $Pb^{206}$ becomes more abundant. Many of the samples containing more than 90 percent $Pb^{206}$ are to the left of the compositional line connecting the average radiogenic $Pb^{207}/Pb^{206}$ ratio of the Plateau ores with the common leads of the Plateau which fall within the small inscribed triangle. The analyses of samples that are plotted to the left of the average compositional line have the largest $Pb^{207}/Pb^{206}$ ratio anomalies.

At least a part of the large anomaly in the radiogenic $Pb^{207}/Pb^{206}$ ratio seems to be due to systematic mass spectrometric errors. Until the amount of these errors can be determined, $Pb^{207}/Pb^{206}$ ages for the Colorado Plateau uranium ores cannot be made. For this reason $Pb^{207}/Pb^{206}$ ages have not been included in this report. Quantitative corrections for the selective loss of radon or for the presence of old radiogenic lead depend solely on very accurate $Pb^{207}/Pb^{206}$ determinations. Therefore, detailed discussion of these corrections is not justified at this time. However, the mean $Pb^{206}/U$ age would not be expected to increase more than 3 million years as a result of these systematic errors. These ages, calculated to the nearest 5 million years, have been presented.

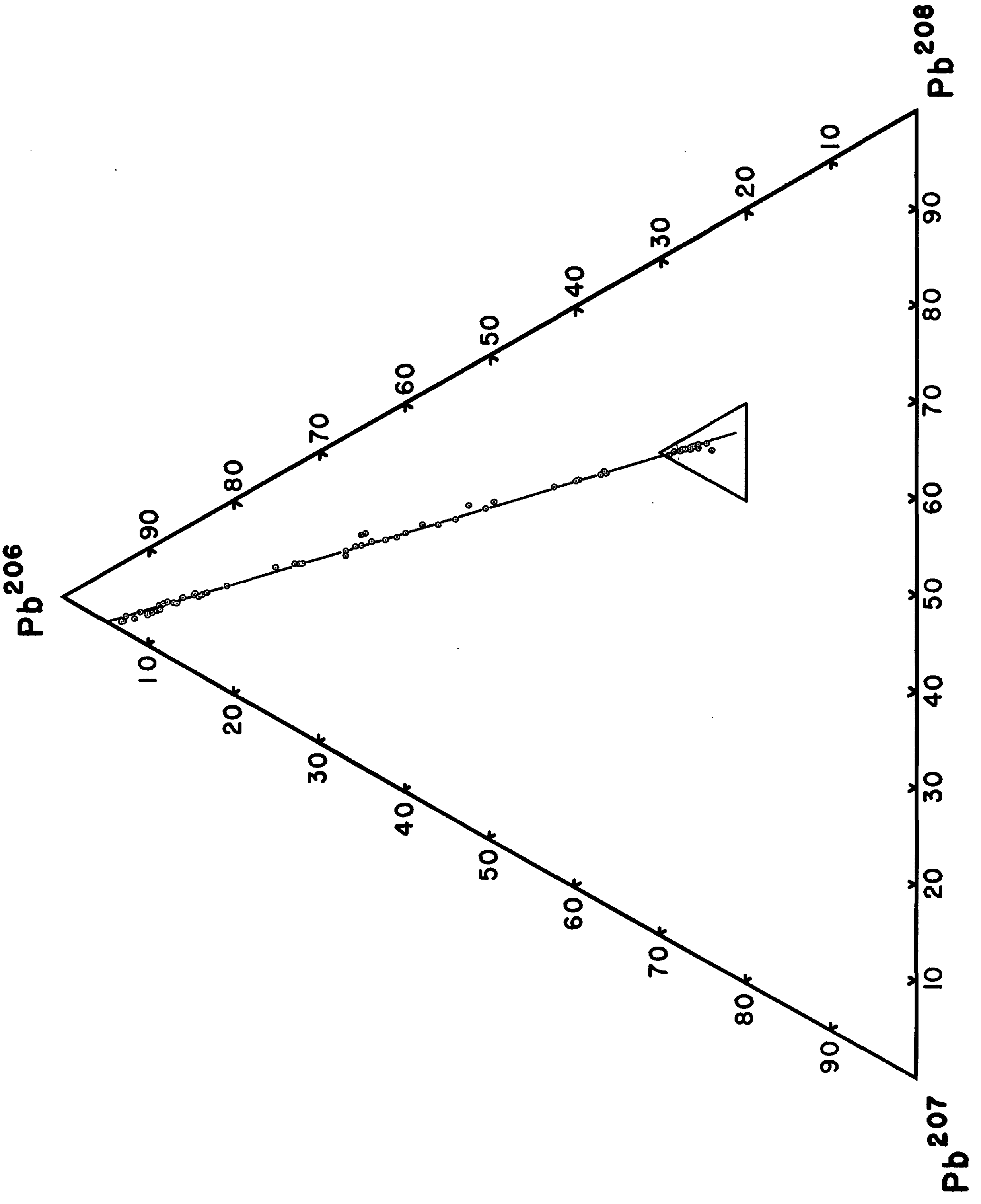

Figure 3.—Triangular diagram of lead isotopes

## Common lead

Almost all lead-uranium and lead-lead age calculations must include a correction for the presence of common lead in the samples because not all of the $Pb^{206}$ and $Pb^{207}$ present was produced by the decay of the $U^{238}$ and $U^{235}$ in the sample. Common lead contains, besides relatively small amounts of $Pb^{204}$ -- the only isotope of lead which is not known to be the product of any radioactive decay series -- varying amounts of $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ in roughly the proportions of 2:2:5. It is believed that much of the $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ in common lead was present at the time of the formation of the earth (Holmes, 1946b, p. 680; 1947, p. 27).

The quantitative effects of common lead corrections on the lead-uranium and lead-lead ages are a function of the $Pb^{206}/U$, $Pb^{207}/U^{235}$ and $Pb^{207}/Pb^{206}$ ratios, the amount of common lead in the ore, and the known or assumed isotopic composition of the lead originally present (common lead plus variable amounts of old radiogenic lead). The lead-uranium ages are usually only moderately affected by the choice of the isotopic composition of the original lead even when a relatively large amount of original lead is present. On the other hand, any uncertainties in the isotopic composition of the original lead can result in large changes in the $Pb^{207}/Pb^{206}$ age. This is true even when only relatively small amounts of original lead are present in the sample.

The range in isotopic composition of common lead is shown in figure 4, an enlargement of the small triangle shown in figure 3. The triangular points (fig. 4) represent the isotopic compositions of the common leads analyzed by Nier (1938, p. 1573, and Nier, Thompson and Murphey, 1941, p. 115). The circles represent the isotopic compositions of the common leads and a few of the ores of the Colorado Plateau that contain large amounts

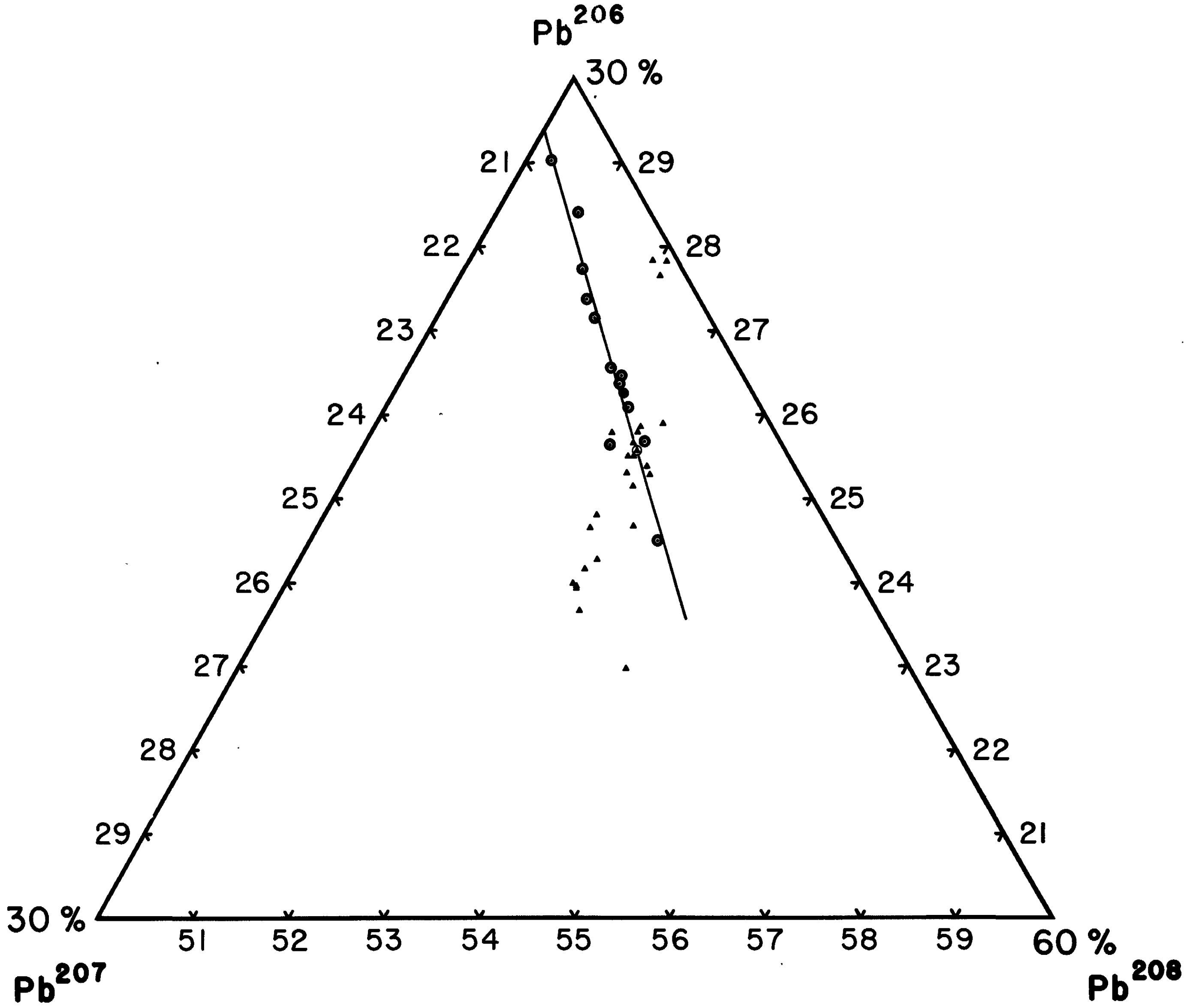

Figure 4.--Triangular diagram of common leads

of common lead. The circle with the inscribed triangle represents the isotopic composition of the common lead in the lead molybdate, wulfenite, and the chloride-vanadate of lead, vanadinite, from the Tucson Mountains, Ariz., analyzed by Nier (1938, p. 1573). We do not know whether there is any significance to the fact that vanadinite from the Tucson Mountains of Miocene age is on the composition line of the Colorado Plateau uranium and vanadium ores apparently of early Tertiary (?) age although the similarities in isotopic composition certainly suggest that all of these samples are in some way genetically related. In any event, the composition of this Tucson Mountains lead has been chosen for many of the age calculations because this lead contains less uranogenic lead than any other lead which could legitimately be considered. This lead, therefore, will give the greatest $Pb^{206}/U$ ages when used in the common-lead correction.

In contrast to variable $Pb^{204}/Pb^{208}$ ratio for the ores containing large amounts of radiogenic lead, the $Pb^{204}/Pb^{208}$ ratio of the common leads from the Colorado Plateau is almost constant and is approximately 0.02651. The relatively uniform $Pb^{204}/Pb^{208}$ ratio of the Plateau common leads is due to the absence of thorium, even in very small amounts, in the ore, and to the relatively low abundance of $Pb^{206}$ in common leads which permits greater accuracy in the isotopic analysis of the lead.

Thorium ($Th^{232}$), the parent of radiogenic $Pb^{208}$, has not been found within the sensitivity limit of the semiquantitative spectrographic determination which is approximately 0.1 percent in the presence of 0.1 to 10 percent uranium. It is difficult to evaluate quantitatively the limits of sensitivity for thorium when uranium is above 10 percent; however, the thorium limit is known to be higher than 0.1 percent. Quantitative chemical analyses of uraninite samples from Happy Jack mine, San Juan County, Utah, and Shinarump No. 1 claim, Grand County, Utah, showed less than 0.01 percent thorium. An isotope dilution analysis of some 30-percent uranium ore from the La Sal No. 2 mine, Mesa County, Colo., showed that the sample contains less than 0.001 percent thorium (George Tilton, personal communication). The almost complete absence of thorium in the uranium ores may be due to the difference in the chemical behavior of thorium and uranium. This absence of thorium may also be due to the fact that these deposits are possibly related to pitchblende veins at depth which usually contain only traces of thorium rather than to average granitic rocks which contain from 3 to 6 times more thorium than uranium.

The customary practice in common-lead corrections is to use the amount of $Pb^{204}$ in the sample that is being studied as an index of the amount of common lead to be deducted. We have not used $Pb^{204}$ as the index but have used $Pb^{208}$ instead in calculating the ages of the Colorado Plateau ores for the three following reasons:

1. The $Pb^{208}$ in the samples is due only to the presence of common lead and is not a result of the decay of thorium ($Th^{232}$).

2. $Pb^{208}$ is approximately 40 times as abundant as $Pb^{204}$ and can be determined with considerably greater precision.

3. The use of the $Pb^{208}$ as an index of common lead yields ages which are greater than the ages obtained when $Pb^{204}$ is used as the common lead index. This is in line with the general objective of calculating a maximum lead-uranium age for the Plateau ores.

## Additions of old radiogenic lead

The variations (fig. 4, triangular points) in the abundance of $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ in common lead that have been analyzed by Nier (1938, p. 1573 and 1941, p. 115) have been conclusively shown to be due to the additions of radiogenic lead (Holmes, 1946b, p. 680; 1947, p. 127).

Although detailed corrections for the presence of old radiogenic lead cannot be made until the mass spectrometric errors are resolved, the maximum, though improbable, reduction in the mean $Pb^{206}/U$ age would not exceed approximately 5 million years.

## Loss of daughter products

An alternative explanation for the distribution of many of the points in figure 3 and the apparent presence of old radiogenic lead in the ores with a mean $Pb^{207}/Pb^{206}$ age of 425 million years is the selective loss or migration of one or more of the daughter products in the $U^{238}$ decay series. Wickman (1942, p. 465) theorized that a preferential loss by diffusion of radon over actinon, the radioactive noble gases, might be expected because of radon's greater half-life. (See table 1.) A detailed correction for loss of radon has not been made because of the uncertainty of the exact values for the radiogenic $Pb^{207}/Pb^{206}$ ratios. A maximum, although improbable, correction for loss of radon would increase the mean $Pb^{206}/U$ age 10 million years but the mean $Pb^{207}/U^{235}$ age would remain unchanged.

## Loss of uranium

It is our belief that, next to the corrections for common lead, the largest source of error in lead-uranium age determinations in many of the carnotite ores is the preferential loss of uranium with respect to lead. The true age of samples corrected for loss of uranium will be younger than the calculated lead-uranium ages. In this preliminary treatment of the data, corrections have not been made for the possible loss of uranium because of the difficulty of determining this factor quantitatively. There is abundant evidence on the Plateau, however, of the alteration and leaching of the ore bodies by surface and ground waters. Therefore, the mean $Pb^{206}/U$ ages that we have calculated are probably older than the actual ages of the specimens.

As Ellsworth (1932, p. 243) has discussed in some detail and Nier (1939b, p. 159) has shown in his paper on the measurement of geologic time, our data confirm the fact that often the apparent age of the alteration products in the immediate vicinity of the primary uranium minerals is greater than that of the primary minerals from which they have been formed. The ages of the alteration products are apparently greater because under most natural environments uranyl salts are more soluble than the comparable lead salts. This results in an enrichment of lead. Phair and Levine's work (1952, p. 4) on the effect of sulfuric acid waters on partly oxidized but black pitchblende shows that in the course of leaching, $UO_2$, radium, and lead were residually concentrated relative to $UO_3$, and the amount of such concentration of both radium and lead was proportional to the amount of uranium leached. Additional evidence from the Plateau of the relatively greater mobility of uranium when compared to lead may be found in several analyses of recent carnotite coatings on joints and fractures which contain 40 to 60 percent uranium and less than 0.01 percent lead (Stieff, Girhard, and Stern, 1950, p. 30).

Preliminary studies by Phoenix (1951, p. 9) of ground waters in the vicinity of some of the Colorado Plateau uranium deposits showed that these waters are weakly alkaline bicarbonate solutions containing a significant amount of uranium. A possible explanation of the erratic ages of the lower-grade samples and the few samples with less than 0.1 percent uranium may be that they have lost disproportionately large amounts of uranium to percolating ground water. Plateau ores of different grade, mineralogic composition, and uranium distribution will be studied in the laboratory by leaching with weakly alkaline solutions.

Many of the events in the geochemical history of the Plateau uranium deposits, involving loss or addition of either uranium or lead, may be shown graphically by plotting the ratio of $Pb^{206}/Pb^{208}$ against the ratio of $U/Pb^{208}$ (fig. 5). Loss of uranium would move the plotted points horizontally to the left, the true age of the sample being less than the plotted one. The $Pb^{206}/Pb^{208}$ ratio corrected for the addition of old radiogenic lead moves the plotted points vertically downward. This movement also results in an age which is less than the plotted one. Radon loss would shift the points vertically upward and increase the age. A similar plot of the ratios of $Pb^{207}/Pb^{208}$ against the ratio of $U^{235}/Pb^{208}$ (fig. 6) shows much the same thing except that there can be no radon loss in this system.

As more detailed data are accumulated from individual deposits, it will be possible by means of similar graphs to determine the approximate amount of uranium that has been lost and composition of the lead originally present in the ore deposit. This information in addition to the data now available should show clearly whether radon loss is a significant process in the modification of the $Pb^{207}/Pb^{206}$ ages and whether old radiogenic lead has been added to the ores at the time of their deposition.

## CALCULATED AGES

### $Pb^{206}/U$ ages of 41 Plateau uranium ores

It is true, not only for the Colorado Plateau uranium ores, but also for any large group of samples used for lead-uranium age studies, that all of the specimens will not give equally reliable ages. The best materials

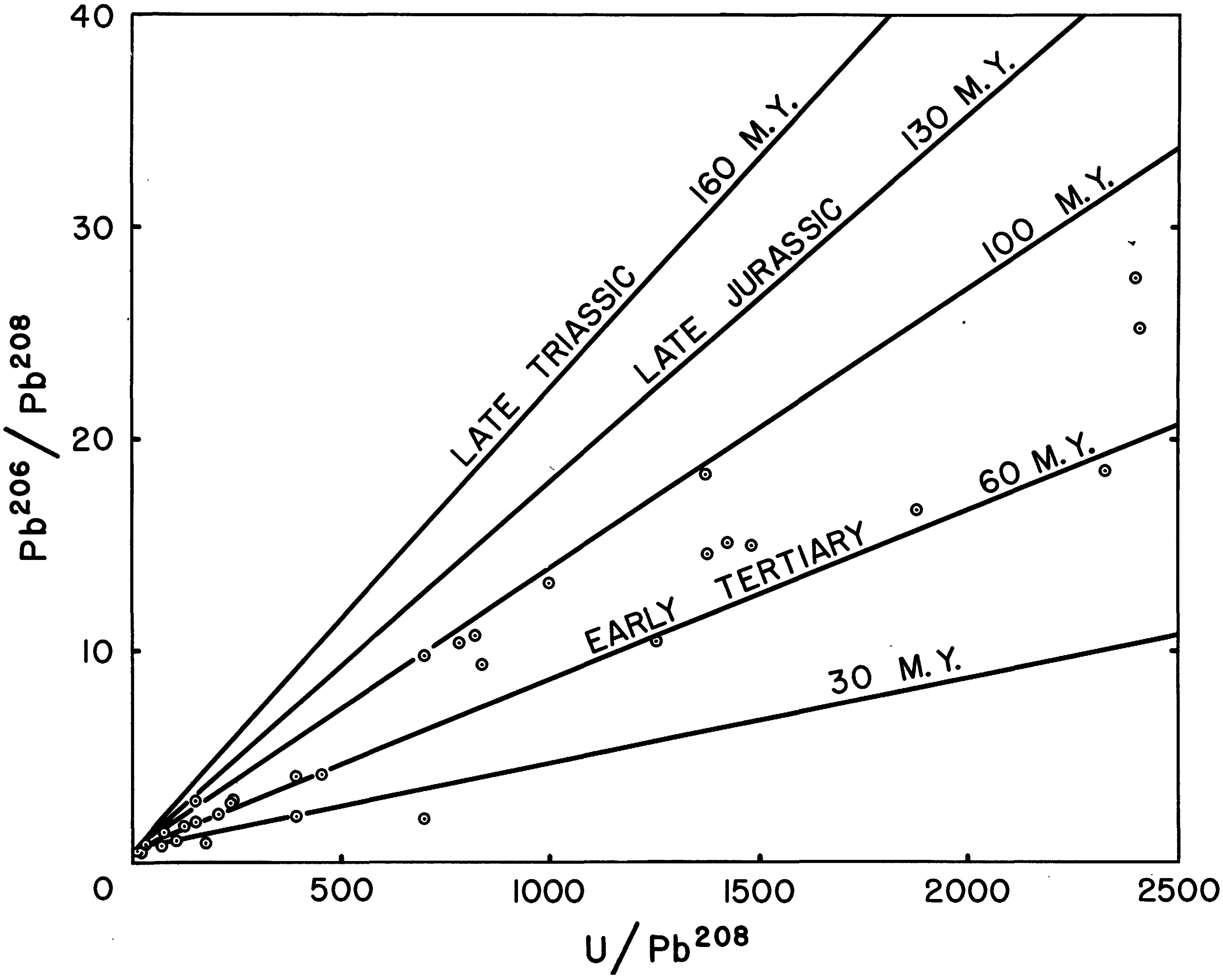

Figure 5.—$Pb^{206}/Pb^{208}$ as a function of $U/Pb^{208}$

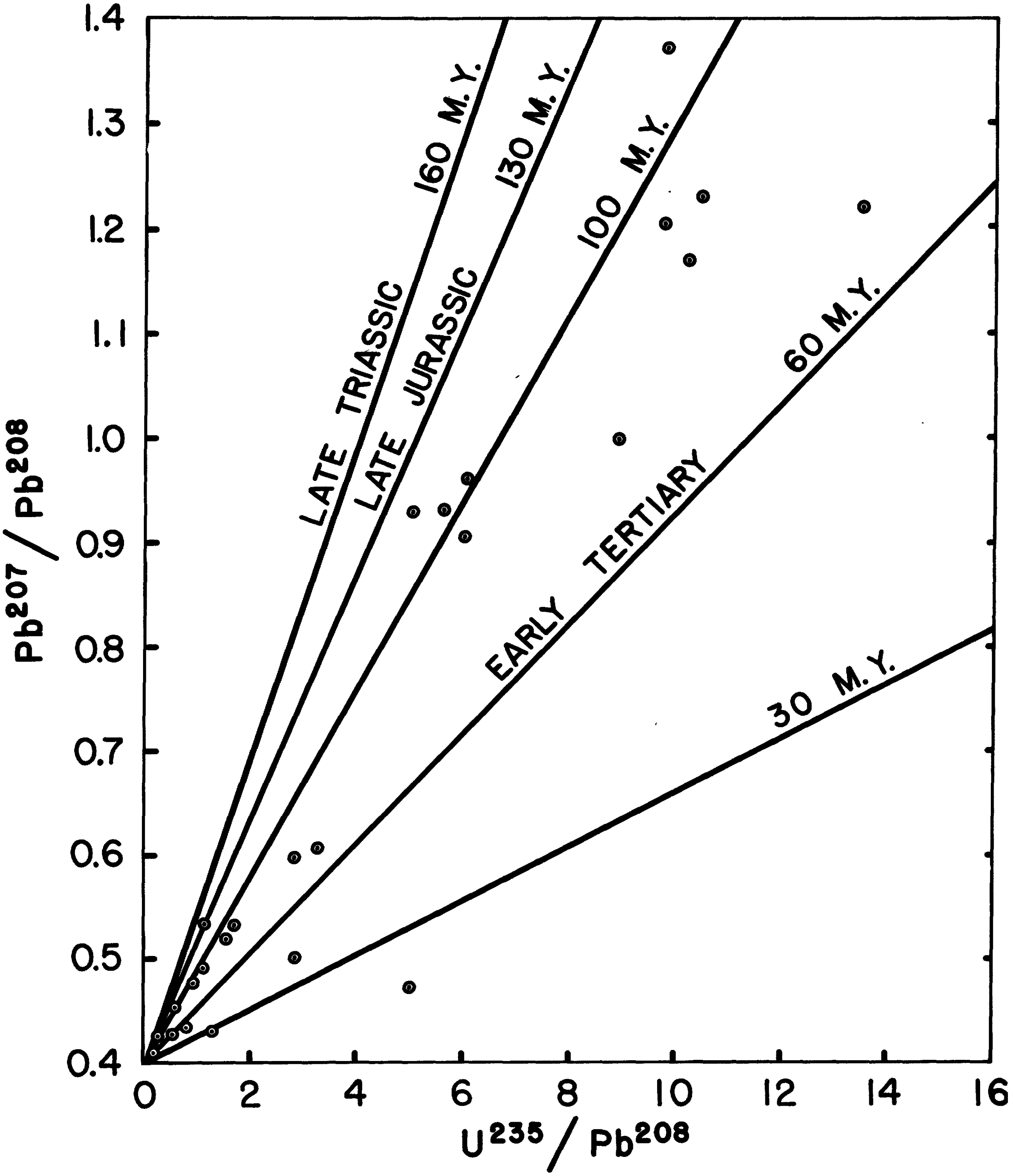

Figure 6.—$Pb^{207}/Pb^{208}$ as a function of $U^{235}/Pb^{208}$

are those which are unaltered and which have a high $UO_2$ content. As has been mentioned, in this preliminary determination of the age of the uranium in the Colorado Plateau ores, no direct consideration is given to the quality of the samples in the calculation of the arithmetic averages. The result of this uncritical grouping of all of the 41 samples studied is that the averages which are given below are probably higher than the actual age of the ore.

A histogram (fig. 7) of the corrected $Pb^{206}/U$ ages for the 41 samples of ore containing more than 0.1 percent uranium shows a pronounced maximum in the 70- to 80-million-year interval. The first quartile, median, and third quartile are also shown because these measures will be used in the next two tables to give some indication of the distribution of the ages that have been determined.

The necessity for isotopic analyses and common-lead corrections is shown (table 2) by the decrease in the mean age of the samples from 270 million years for total lead to 68 million using the isotopic composition of the Plateau lead mineral nearest the deposit (best) from which the ore sample was taken. The wide range for both total lead and total $Pb^{206}$ ages is shown by the fact that the mean age is greater than the third quartile.

Table 2.--Pb/U and $Pb^{206}/U$ ages of 41 Colorado Plateau uranium ores (in millions of years)

| | Mean | 1st quartile | Median | 3d quartile |
|---|---|---|---|---|
| Total Pb/U | 270 | 77.5 | 110 | 165 |
| Total $Pb^{206}/U$ | 120 | 67.5 | 85 | 105 |
| Radiogenic $Pb^{206}/U$ (Vanadinite) 1/ | 71 | 60. | 75 | 90 |
| Radiogenic $Pb^{206}/U$ (Best) | 68 | 60. | 75 | 90 |

1/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

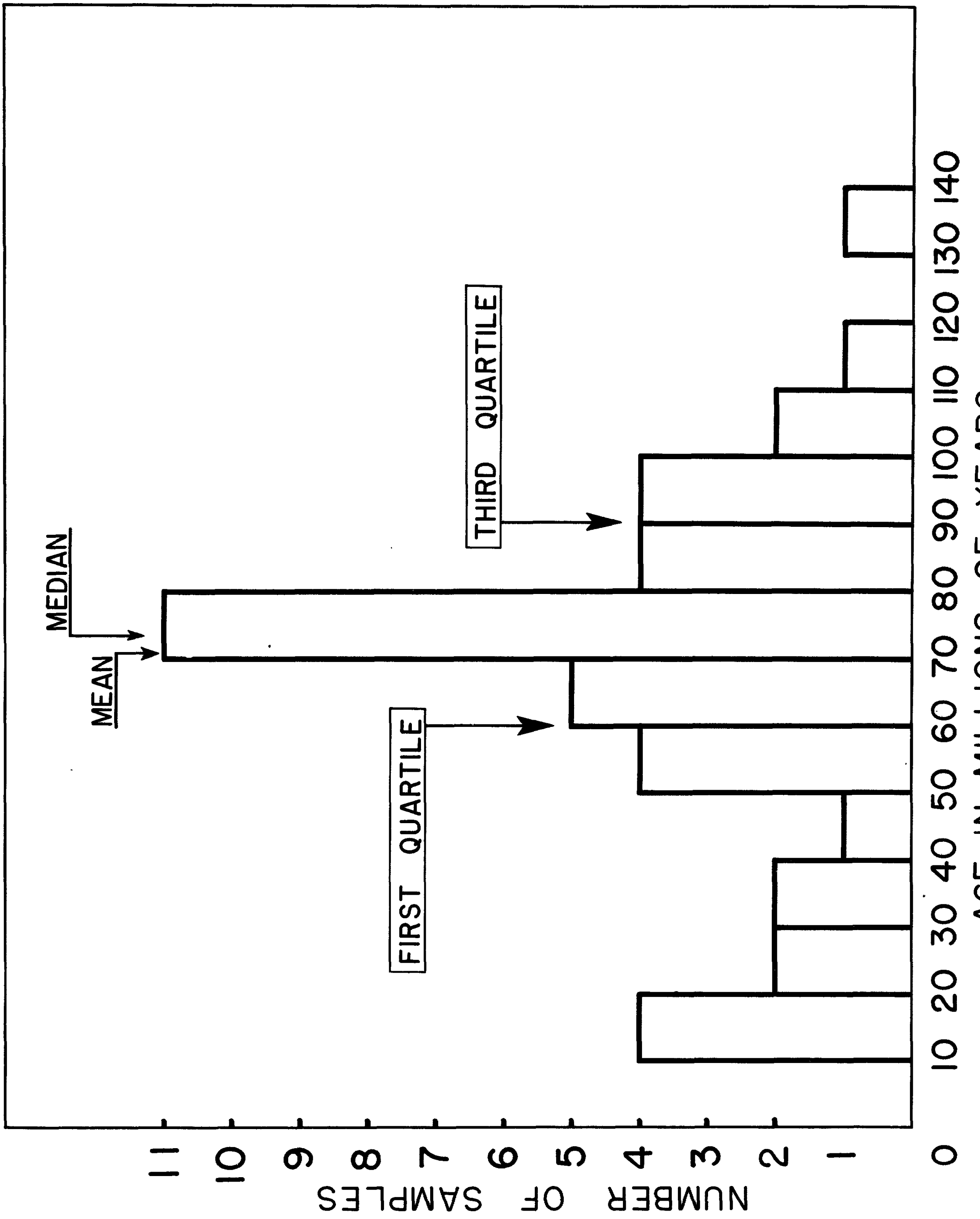

Figure 7.—Histogram of results of age calculations

## $Pb^{207}/U^{235}$ ages of 41 Plateau uranium ores

Most of the $Pb^{207}/U^{235}$ ages (table 3) are greater than the $Pb^{206}/U$ ages because the systematic mass spectrometric errors result in apparent $Pb^{207}$ abundances which are greater than the actual abundances of this isotope. The total $Pb^{207}/U^{235}$ age is greater than the total Pb/U age because samples containing large amounts of common lead contain a greater percentage of $Pb^{207}$ than do samples of pure radiogenic lead. The similarity of the mean "best" lead and vanadinite $Pb^{207}/U^{235}$ ages reflects the relatively small variations that have been found in the $Pb^{207}/Pb^{208}$ ratios of the Plateau common leads.

Table 3.--Total and corrected $Pb^{207}/U^{235}$ ages of 41 Colorado Plateau ores (in millions of years)

| | Mean | 1st quartile | Median | 3d quartile |
|---|---|---|---|---|
| Total $Pb^{207}/U^{235}$ 1/ | 429 | 119 | 168 | 339 |
| Radiogenic $Pb^{207}/U^{235}$ (Vanadinite) 2/ | 82 | 66.8 | 86.9 | 103.2 |
| Radiogenic $Pb^{207}/U^{235}$ (Best) | 82 | 66.5 | 88.6 | 103.7 |

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1/ Data on 40 samples

2/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

## $Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of samples grouped by grade

The tabulation of the samples according to grade (table 4) shows a small difference in mean $Pb^{206}/U$ ages. Generally the lower-grade uranium ores contain relatively larger amounts of common lead. The $Pb^{206}/U$ ages of this group, therefore, would be lowered the most by a better choice of the common lead used for the common lead correction. Also, this group would be most affected by a uniform loss of uranium due to leaching by ground waters.

Table 4.--$Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of 41 Colorado Plateau uranium ore samples grouped by grade of sample

| Grade of sample | Number of samples | Mean $Pb^{206}/U$ age in MY 1/ | Mean $Pb^{207}/Pb^{206}$ ratio |
|---|---|---|---|
| $>$ 10% U | 16 | 68 | 0.0576 |
| 1.0 - 10.0% U | 8 | 70 | 0.0568 |
| 0.1 - 1.0% U | 17 | 75 | 0.0533 |

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1/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

The lower $Pb^{207}/Pb^{206}$ ratio for samples containing 0.1 to 1.0 percent uranium may be due to a smaller radon loss but more probably it reflects both the greater common lead correction and the greater accuracy of the mass spectrometer measurements. The inability of the mass spectrometer completely to resolve the $Pb^{204}$, $Pb^{207}$, and $Pb^{208}$ peaks from the $Pb^{206}$ peak is shown by the larger $Pb^{207}/Pb^{206}$ ratios in those samples containing both the largest amounts of $Pb^{206}$ and uranium.

## $Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of samples grouped by type

The largest spread in mean $Pb^{206}/U$ ages is found by grouping the samples into mill pulps and small specimens (table 5). The mill pulp samples were obtained from the U. S. Vanadium Corporation's ore sampling plants. Each sample is a split from approximately 235 tons or more of ore from a single ore body. The small samples are hand specimens especially selected in the mines for isotopic lead-uranium age studies. The greater mean $Pb^{206}/U$ ages of the large mill pulps compared with the small samples correspond to the greater ages of the samples which contain less than 1.0 percent uranium mentioned in the last paragraph. The grade of the mill pulps is between 0.18 and 0.49 percent uranium. Also, with the exception of the three Calamity mill pulps, more than 40.9 percent of the lead they contain is common lead.

Table 5.--$Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of 41 Colorado Plateau uranium ore samples grouped by type of sample

| Type of sample | Number of samples | Mean $Pb^{206}/U$ age in MY 1/ | Mean $Pb^{207}/Pb^{206}$ ratio |
|---|---|---|---|
| Mill pulp splits (235 or more tons) | 9 | 96 | 0.0523 |
| Small samples (5 pounds or less) | 32 | 64 | 0.0566 |

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1/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

The greater age of the ores which have lost uranium is shown by the inclusion in the mill-pulp group of one pulp sample from a surface deposit which was mined as an open cut. This pulp gave a $Pb^{206}/U$ age of 120 million years and the open cut showed abundant evidence of the selective loss of uranium by recent percolating ground waters. The remaining mill pulps might also be expected to show some effect of loss of uranium although they come from less exposed deposits and thus their ages would not be as great as the sample from the open cut.

In addition, the mill pulps have lower $Pb^{207}/Pb^{206}$ ratios than the small samples. This may be due in part to the following facts: (1) they contain more common lead, (2) the mass spectrometric analyses are better in this range, and (3) these samples have lost less radon and/or have received less old radiogenic lead.

## $Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of samples grouped by stratigraphic position

The mean $Pb^{206}/U$ ages of the samples tabulated according to the stratigraphic unit in which the deposits are found (table 6) does not show any correlation with the age of the enclosing sediments. In spite of the uncertainty concerning the $Pb^{207}/Pb^{206}$ ratio it is interesting that the mean ratios do not show any evidence of increasing as the age of the sediments increases. The variation of only 0.4 percent in the mean $Pb^{207}/Pb^{206}$ ratio of the Morrison and Shinarump ores suggests that the ores in both formations were deposited at the same time and/or came from similar sources at depth.

Table 6.--$Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of 41 Colorado Plateau uranium ore samples grouped by stratigraphic position

| Formation | Age of stratigraphic unit in MY 1/ | Number of samples | Mean $Pb^{206}/U$ age in MY 2/ | Mean $Pb^{207}/Pb^{206}$ ratio |
|---|---|---|---|---|
| Morrison | 127 | 34 | 72 | 0.0550 |
| Entrada | 130 - 140 | 3 | 50 | 0.0627 3/ |
| Shinarump | 152 | 4 | 73 | 0.0548 |

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1/ Holmes, Arthur, The construction of a geological time-scale: Geol. Soc. Glasgow. Trans., vol. 21, pt. 1, p. 145, 1946.

2/ Isotopic composition of the lead in vanadinite used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

3/ This mean $Pb^{207}/Pb^{206}$ ratio is appreciably affected by the assumed isotopic composition of the common lead used because of the large percentage of common lead in the samples.

The $Pb^{206}/U$ and $Pb^{207}/Pb^{206}$ ratios for the Entrada ores are not very reliable because very large common lead corrections were made. A common lead with an isotopic composition similar to the lead from a galena specimen taken at Placerville, Colo., results in much lower $Pb^{207}/Pb^{206}$ ratios for two of the three samples.1/

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1/ An unsuspected relation between the deposits of argentiferous galena in the Pony Express limestone and the underlying Entrada uranium-bearing "roscoelite" ores of the Placerville area is very strongly suggested by the systematic changes in the isotopic composition of the lead from the two different types of ores. The composition of the Placerville galena (Appendix 3, Sample GS 5) is bracketed by the composition of the leads from the ores of the Bear Creek mine and adjacent Primus claim (Appendix 3, Sample GS 22 and 25). This galena contains more radiogenic lead than any other galena whose isotopic composition has been published. The implication that the Placerville argentiferous galena deposit might also contain workable amounts of uranium should be carefully examined.

## $Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of samples grouped by mineralogic composition

A tabulation of the samples according to the major uranium-bearing mineral present in the ore is given in table 7.

The $Pb^{206}/U$ ages of the carnotite ores range from 20 million years to 140 million years. From the field relations of individual samples as well as their chemistry we believe that the greater ages reflect selective loss of uranium. The lower ages of the carnotite ores, however, may be real and may result wholly or in part from actual differences in age of some parts of the deposits. Alteration of the early Tertiary primary ores and redeposition of some of the secondary carnotite at different times during the Tertiary should be considered.

The ages of the vanadiferous hydromica ores are doubtful and it cannot be stated at this time if the lower mean age is significant. Additional work on these ores is planned. An asphaltic ore containing uraninite from Temple Mountains and a black ore containing an undescribed uranium mineral from La Sal No. 2 mine give $Pb^{206}/U$ ages of 80 and 90 million years, respectively.

Table 7.--$Pb^{206}/U$ ages and $Pb^{207}/Pb^{206}$ ratios of 41 Colorado Plateau uranium ore samples grouped by mineralogic composition

| Mineralogic composition | Number of samples | Mean $Pb^{206}/U$ age in MY 1/ | Mean $Pb^{207}/Pb^{206}$ ratio |
|---|---|---|---|
| Carnotite | 34 | 72 | 0.0552 |
| Vanadiferous hydromica | 3 | 50 | 0.0627 2/ |
| Undescribed uranium minerals | 2 | 85 | 0.0568 |
| Uraninite | 2 | 70 | 0.0530 |

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1/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

2/ This mean $Pb^{207}/Pb^{206}$ ratio is appreciably affected by the assumed isotopic composition of the common lead used because of the large percentage of common lead in the samples.

We believe that the age determinations which we have made on the Happy Jack and Shinarump No. 1 uraninite specimens, 65 and 75 million years, respectively, (Stieff and Stern, 1952, p. 707) are the most reliable that have been made on Colorado Plateau uranium ores. The mean $Pb^{206}/U$ age of 70 million years for the two Shinarump uraninite samples is believed to be within 10 million years of the true age of the samples. The Happy Jack specimen had the highest specific gravity (9.1), was the freshest in appearance, and contained the smallest amounts of common lead. The anomalous $Pb^{207}/Pb^{206}$ ratio for this sample cannot be readily explained on the basis of a required radon loss of 5.5 percent. The measured loss of radon from the massive uraninite from the Happy Jack mine is less than 1.0 percent under atmospheric conditions.

Although adequate $Pb^{206}/U^{238}$ ages for the end of the Trassic and Jurassic are not available, the beginning of the Tertiary has been dated by Holmes (1946a, p. 145) who recalculated the $Pb^{206}/U^{238}$ age of two Colorado Front Range pitchblendes as 57.3 and 59.8 million years. Two additional Front Range pitchblendes which have been analyzed in this laboratory give $Pb^{206}/U$ ages of 60 and 70 million years. The average age of our uraninite samples from the Shinarump conglomerate is 70 million years and both these samples show slightly high $Pb^{207}/Pb^{206}$ ratios. If old radiogenic lead is partly responsible for the high $Pb^{207}/Pb^{206}$ ratios, we would expect the true ages of the Shinarump uraninites to be somewhat less than 65 million years. The similarity in age of the pitchblendes from sedimentary rocks in the Colorado Plateau and in the vein deposits in the Colorado Front Range is striking.

## SUMMARY AND CONCLUSIONS

The calculation of the age of the Plateau uranium ores is subject to the following corrections:

1. Analytical errors.
2. The presence of common lead in the ore.
3. The presence of old radiogenic lead in the ore.
4. The migration of certain radioactive daughter products, such as radon.
5. The loss of uranium due to alteration of the ore by ground waters.

The analytical chemical errors result in an uncertainty in the mean $Pb^{206}/U$ age of approximately ± 3 million years. However, the mean lead-uranium ages presented have been given without limits because of our inability at this time to evaluate quantitatively several of the remaining corrections.

These ages, therefore, have been calculated so that any changes in them due to more probable common lead corrections, to the presence of old radiogenic lead, or due to loss of uranium will only lower the mean age. The systematic mass spectrometric errors should not increase the mean $Pb^{206}/U$ age by more than 3 million years. An increase of approximately 10 million years in the mean $Pb^{206}/U$ age can be expected only if radon loss is demonstrated to have been a major process on the Plateau and the only cause of the $Pb^{207}/Pb^{206}$ ratio anomaly.

The mean $Pb^{206}/U$ age after correction for common lead is 71 million years. The isotopic composition of the common lead used in obtaining this mean age was determined by Nier. A comparison of our Plateau common leads with the analysis of vanadinite from the Tucson Mountains, Ariz., (Miocene age) showed that the latter common lead contains less radiogenic $Pb^{206}$ and $Pb^{207}$ than any of the Colorado Plateau common leads that we have studied. These corrected ages will therefore be maximum ages and any further small improvements in common lead corrections will only lower the mean $Pb^{206}/U$ age of 71 million years.

Although young $Pb^{207}/Pb^{206}$ ages are not reliable and therefore have not been presented in this report, the partly corrected but still anomalous $Pb^{207}/Pb^{206}$ ratios have been included because they may contain valuable information on the source of the ore-forming solutions and the geologic processes related to the history of the ore. These anomalous ratios have been given without precision limits because of the difficulty of quantitatively evaluating the very significant but small mass spectrometric errors, the actual composition of the common lead in the ore, the presence of old radiogenic lead, and the migration of daughter products. If part of the anomalously high $Pb^{207}/Pb^{206}$ ratios are shown to be evidence for the addition of old radiogenic lead, then the source areas of the ore-bearing solutions from which the Plateau deposits were formed will probably be found at depth, and the lead-uranium and lead-lead ages will drop to approximately 65 million years. If, on the other hand, the high $Pb^{207}/Pb^{206}$ ratios are shown to be due to the selective loss of radon, the mean $Pb^{206}/U$ ages will increase to a maximum of approximately 82 million years.

Of particular interest is the similarity of the mean $Pb^{206}/U$ ages (72 and 73 million years) and $Pb^{207}/Pb^{206}$ ratios (0.0550 and 0.0548) of the ores from deposits in the late Triassic and late Jurassic sediments. The sediments are thought to differ in age by about 30 million years and the late Jurassic rocks are believed to be approximately 130 million years old. The absence of any correlation between the age of the enclosing sediments and the calculated ages and ratios of the ores they contain not only suggests a single period of ore formation but also similar or perhaps common sources for both the uranium and the lead originally present in the ore.

The age determinations made on the Happy Jack and Shinarump No. 1 uraninite specimens, 65 and 75 million years, respectively, are the most reliable that we have made on any Plateau uranium ore. Of the two, the Happy Jack specimen had the highest specific gravity, was the freshest in appearance, and contained the smallest amounts of common lead. Its $Pb^{206}/U$ age of 65 million years is believed to be correct within approximately 5 million years. The age of the enclosing late Triassic sediments, approximately 160 million years, is more than twice as great as the age of the ore these sedimentary rocks contain. This discrepancy of almost 100 million years is in striking contrast to the almost identical mean age of 60.5 million years of four early Tertiary Colorado Front Range pitchblende samples, two analyzed by Nier and two determined in this laboratory.

If the true age of the ore is less than our highest mean $Pb^{207}/U^{235}$ age of 82 million years, and we believe that it is, two interpretations of the origin and history of the Colorado Plateau uranium deposits can be made:

1. Uranium was deposited either at the same time or shortly after the enclosing Jurassic and Triassic sediments in which it is found were laid down, or the uranium was deposited in one of the overlying Cretaceous sediments. At the close of the Cretaceous or at the beginning of the Tertiary, the uranium and the radiogenic lead which had been formed were taken into solution and the uranium was eventually redeposited in approximately its present sites. The deficiency of radiogenic lead for a syngenetic ore indicates that most of the radiogenic lead formed prior to this Tertiary event could not have been redeposited in or near ore. The common lead, however, which was originally deposited in the sediments with the uranium was redeposited in the present sites. The selective removal of the radiogenic $Pb^{206}$ and $Pb^{207}$ isotopes, formed prior to the end of the Cretaceous, from the ore solutions poses an extremely difficult problem, the solution of which is not immediately apparent. During the period of dissection and erosion, the deposits were partly altered, partly leached, and partly redistributed by circulating ground waters.

2. A simpler and more probable interpretation of the lead-isotope data is that at the close of the Cretaceous or the beginning of the Tertiary uranium, common lead, a little old radiogenic lead, vanadium, and other metals were introduced into the sediments of the Plateau. These metals probably had similar sources or perhaps a common source, to be found at depth. The original uranium and vanadium ore minerals were probably oxides or mixtures of

oxides. During the period of dissection and erosion, the deposits were partly altered, partly leached and partly redistributed by circulating ground waters.

The immediate objective of this age study of the Colorado Plateau uranium ores has been to determine whether these ores were deposited during the Triassic and Jurassic periods or whether all of the deposits were formed at the end of the Cretaceous or the beginning of the Tertiary period. An unequivocal answer cannot be given at this time, although our data strongly suggest that the present deposits are of late Cretaceous age or younger. Regardless of the final interpretation of the origin and history of the Colorado Plateau uranium deposits, it is certain that the conditions prevailing during the close of the Cretaceous and the beginning of the Tertiary must have played an important part in localizing the present deposits. The partial control of the ore solutions by both major and minor sedimentary features is easily demonstrated. The relations of the ore to the late Cretaceous and early Tertiary intrusions of igneous rocks, movement of the salt, as well as to folding and faulting are not as clear, but perhaps the present re-examination of these possible relationships may show a connection between the regional structure and the ore deposits. Also, the possibility of development of the ore with depth might be considered, particularly an investigation of the Salt Wash sandstones below the present "ore zone". If the ore solutions were introduced from below, it is possible that the potentialities of the Colorado Plateau as a uraniferous province have just been touched.

# APPENDIX 1

## Colorado Plateau uranium ores used for age calculations 1/

### Shinarump conglomerate

| Sample no. | | Location | Mineralogic composition | $Pb^{206}/U$ age in MY 2/ | Corrected $Pb^{207}/Pb^{206}$ |
|---|---|---|---|---|---|
| GS | 63 | Shinarump No. 1 claim, Seven Mile Canyon, Grand County, Utah | Uraninite | 75 | 0.0558 |
| GS | 64 | Happy Jack mine, San Juan County, Utah | Uraninite | 65 | 0.0501 |
| GS | 13 | Monument No. 2 mine, Apache County, Arizona | Carnotite type | 75 | 0.0570 |
| GS | 66 | Camp Bird No. 13 mine, Temple Mountain, Emery County, Utah | Asphaltic type | 80 | 0.0560 |

### Entrada sandstone

| Sample no. | | Location | Mineralogic composition | $Pb^{206}/U$ age in MY | Corrected $Pb^{207}/Pb^{206}$ 3/ |
|---|---|---|---|---|---|
| GS | 22 | Bear Creek mine, San Miguel County, near Placerville, Colorado | Vanadiferous hydromica | 20 | 0.0578 |
| GS | 28 | Vanadous No. 1 mine, San Miguel County, Colorado | Vanadiferous hydromica | 40 | 0.0603 |
| GS | 24 | Primus claim, San Miguel County, Colorado | Vanadiferous hydromica | 90 | 0.0692 |

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1/ The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, A. O., Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573, 1938.

2/ Age expressed to nearest 5 million years.

3/ The $Pb^{207}/Pb^{206}$ ratio is appreciably affected by the assumed isotopic composition of the common lead present because of the large percentage of common lead in the samples.

## Morrison formation

| Sample no. | | Location | Mineralogic composition | $Pb^{206}/U^{238}$ age in MY | Corrected $Pb^{207}/Pb^{206}$ |
|---|---|---|---|---|---|
| GS | 20 | Roc Creek mine, Montrose County, Colorado | Carnotite type | 60 | 0.0537 |
| GS | 65 | La Sal No. 2 mine, Mesa County, Colorado | New uranium-vanadium mineral | 90 | 0.0570 |
| GS | 21 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 75 | 0.0523 |
| GS | 31 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 75 | 0.0617 |
| GS | 33 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 85 | 0.0601 |
| GS | 34 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 75 | 0.0599 |
| GS | 35 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 105 | 0.0547 |
| GS | 42* | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 100 | 0.0560 |
| GS | 43 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 140 | 0.0608 |
| GS | 10 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 70 | 0.0610 |
| LRS | 28 | Calamity No. 13 mine, Mesa County, Colorado | Carnotite type | 75 | 0.0605 |
| GS | 41* | Calamity No. 21 mine, Mesa County, Colorado | Carnotite type | 90 | 0.0541 |

* Mill pulp sample

| Sample no. | Location | Mineralogic composition | $Pb^{206}/U^{238}$ age in MY | Corrected $Pb^{207}/Pb^{206}$ |
|---|---|---|---|---|
| GS 40* | Calamity No. 27 mine, Mesa County, Colorado | Carnotite type | 95 | 0.0526 |
| LRS 63 no. 2 | Club mine, Montrose County, Colorado | Carnotite type | 75 | 0.0584 |
| GS 11 | Club mine, Montrose County, Colorado | Carnotite type | 60 | 0.0593 |
| GS 12 | Club mine, Montrose County, Colorado | Carnotite type | 70 | 0.0582 |
| GS 48* | Mill No. 1 mine, Montrose County, Colorado | Carnotite type | 85 | 0.0531 |
| GS 30 | Rock Raven No. 3 mine, Montrose County, Colorado | Carnotite type | 15 | 0.0437 |
| GS 47* | Coloradium mine, Montrose County, Colorado | Carnotite type | 75 | 0.0537 |
| GS 39 no. 3* | Long Park No. 10 mine, Montrose County, Colorado | Carnotite type | 110 | 0.0467 |
| GS 18 | Bitter Creek mine, Montrose County, Colorado | Carnotite type | 70 | 0.0525 |
| GS 15 no. 1 | Jo Dandy mine, Montrose County, Colorado | Carnotite type | 20 | 0.0653 |
| GS 15 no. 2 | Jo Dandy mine, Montrose County, Colorado | Carnotite type | 60 | 0.0594 |
| GS 19 no. 1 | Wild Steer mine, Montrose County, Colorado | Carnotite type | 40 | 0.0466 |
| GS 19 no. 2 | Wild Steer mine, Montrose County, Colorado | Carnotite type | 20 | 0.0464 |
| LRS 64 no. 1 | Bob Tail mine, Montrose County, Colorado | Carnotite type | 30 | 0.0607 |

* Mill pulp samples

| Sample no. | Location | Mineralogic composition | $Pb^{206}/U^{238}$ age in MY | Corrected $Pb^{207}/Pb^{206}$ |
|---|---|---|---|---|
| GS 49* | Red Bird mine, Montrose County, Colorado | Carnotite type | 75 | 0.0518 |
| GS 14 | Mine D mine, Montrose County, Colorado | Carnotite type | 100 | 0.0543 |
| GS 17 | Butterfly mine, Montrose County, Colorado | Carnotite type | 35 | 0.0542 |
| GS 23 | Raven mine, Montrose County, Colorado | Carnotite type | 70 | 0.0605 |
| GS 50* | Charles T No. 2 mine, San Miguel County, Colorado | Carnotite type | 120 | 0.0521 |
| GS 16 | Radium No. 6 mine, San Miguel County, Colorado | Carnotite type | 60 | 0.0530 |
| LRS 20 no. 2 | Radium No. 6 mine, San Miguel County, Colorado | Carnotite type | 30 | 0.0511 |
| GS 51* | Radium No. 8 mine, San Miguel County, Colorado | Carnotite type | 100 | 0.0502 |

* Mill pulp samples

## Common lead

| Sample no. | | Location | Mineral | Formation |
|---|---|---|---|---|
| GS | 1 | Rifle mine, Garfield County, Colorado | Galena | Entrada sandstone ? |
| GS | 2 | Garfield mine, Garfield County, Colorado | Galena | Entrada sandstone ? |
| GS | 7 | Bitter Creek mine, Montrose County, Colorado | Descloizite ? | Salt Wash sandstone member of Morrison formation |
| GS | 9 | La Sal No. 1 mine, San Juan County, Utah | ? | Salt Wash sandstone member of Morrison formation |
| GS | 67 | Wilson Mesa | Galena | Dakota sandstone |
| GS | 68 | Cougar mine, Lower group, San Miguel County, Colorado | Galena | Salt Wash sandstone member of Morrison formation |
| GS | 8 | Gap Claim, San Miguel County, Colorado | ? | Salt Wash sandstone member of Morrison formation |
| GS | 5 | Philadelphia Claim, Placerville, San Miguel County, Colorado | Galena | Pony Express limestone |
| GS | 6 | Argentine mines, San Juan County, Colorado | Galena | ? |
| GS | 70 | Blanding water tunnel, Abajos Mountains, San Juan County, Utah | Galena | ? |

# APPENDIX 2

## Lead and uranium content of uranium ores used for age calculations 1/

| Sample number | g Pb/g sample | g U/g sample |
|---|---|---|
| GS 10 | 0.0033 | 0.325 |
| 11 | 0.0032 | 0.322 |
| 12 | 0.0033 | 0.148 |
| 13 | 0.00183 | 0.1554 |
| 14 | 0.00176 | 0.1168 |
| 15 #1 | 0.0008 | 0.311 |
| 15 #2 | 0.00166 | 0.1910 |
| 16 | 0.00128 | 0.1443 |
| 17 | 0.000705 | 0.0740 |
| 18 | 0.000052 | 0.0036 |
| 19 #1 | 0.0011 | 0.0463 |
| 19 #2 | 0.000116 | 0.0086 |
| 20 | 0.000060 | 0.0047 |
| 21 #1 | 0.000093 | 0.0077 |
| 22 | 0.000552 | 0.0064 |
| 23 | 0.00062 | 0.0341 |
| 24 | 0.00118 | 0.0022 |
| 28 | 0.000102 | 0.0031 |
| 30 | 0.000023 | 0.0046 |
| 31 | 0.000300 | 0.0256 |
| 33 | 0.000402 | 0.0314 |
| 34 | 0.000254 | 0.0228 |
| 35 #1 | 0.000313 | 0.0209 |
| 39 #3 | 0.000155 | 0.0021 |
| 40 | 0.000068 | 0.0043 |
| 41 | 0.000074 | 0.0049 |
| 42 | 0.000052 | 0.0031 |
| 43 | 0.0047 | 0.241 |
| 47 | 0.000062 | 0.0033 |
| 48 | 0.000089 | 0.0046 |
| 49 | 0.00057 | 0.0027 |
| 50 | 0.000052 | 0.0018 |
| 51 | 0.000132 | 0.0034 |
| 63 | 0.0143 | 0.559 |
| 64 | 0.0074 | 0.7346 |
| 65 | 0.0014 | 0.102 |
| 66 | 0.00039 | 0.0290 |
| LRS 20 #2 | 0.0015 | 0.326 |
| 28 #1 | 0.0038 | 0.360 |
| 63 #2 | 0.0031 | 0.254 |
| 64 #1 | 0.0014 | 0.346 |

1/ Analysts: R. G. Milkey, Harry Levine, and Frank Cuttitta, U. S. Geological Survey

# APPENDIX 3

## Isotopic composition of Colorado Plateau lead from uranium ores and lead minerals [1]

Atom percent abundance of lead isotopes [2]

| Sample | 204 | 206 | 207 | 208 |
|---|---|---|---|---|
| GS 1 | 1.38 ± .01 | 26.10 ± .05 | 20.97 ± .02 | 51.55 ± .05 |
| 2 | 1.37 ± .03 | 26.07 ± .05 | 21.00 ± .03 | 51.56 ± .08 |
| 5 | 1.363 ± .008 | 27.00 ± .05 | 20.86 ± .03 | 50.77 ± .05 |
| 6 | 1.40 ± .01 | 25.29 ± .04 | 21.48 ± .03 | 51.84 ± .04 |
| 7 #1 | 1.37 ± .02 | 25.73 ± .08 | 21.09 ± .09 | 51.81 ± .02 |
| 7 #2 | 1.36 ± .02 | 25.78 ± .05 | 20.97 ± .18 | 51.90 ± .07 |
| 8 | 1.39 ± .05 | 28.02 ± .08 | 20.45 ± .04 | 50.14 ± .05 |
| 9 #1 | 1.38 ± .01 | 26.20 ± .03 | 21.02 ± .02 | 51.41 ± .04 |
| 9 #2 | 1.38 ± .01 | 26.20 ± .03 | 21.06 ± .03 | 51.36 ± .04 |
| 10 | 0.029 ± .003 | 92.92 ± .05 | 6.05 ± .07 | 1.00 ± .02 |
| 11 | 0.227 ± .004 | 83.76 ± .03 | 8.00 ± .02 | 8.01 ± .02 |
| 12 | 0.820 ± .013 | 55.57 ± .08 | 14.34 ± .03 | 29.27 ± .10 |
| 13 | 0.169 ± .012 | 86.87 ± .02 | 7.16 ± .04 | 5.80 ± .02 |
| 14 | 0.150 ± .003 | 88.40 ± .03 | 6.64 ± .02 | 4.82 ± .02 |
| 15 #1 | 0.159 ± .009 | 91.40 ± .03 | 6.64 ± .03 | 1.80 ± .01 |
| 15 #2 | 0.034 ± .003 | 93.23 ± .01 | 5.87 ± .02 | 0.871 ± .013 |
| 16 | 0.138 ± .003 | 88.59 ± .02 | 6.51 ± .02 | 4.76 ± .02 |
| 17 | 0.746 ± .008 | 59.41 ± .11 | 13.35 ± .06 | 26.50 ± .09 |

[1] Analyses by Carbide and Carbon Chemical Company, Y-12 Plant, Mass Assay Laboratory, Oak Ridge, Tenn.

[2] The limits of precision are calculated so that 95 percent of any new determination will fall within the limits given.

| Sample | 204 | 206 | 207 | 208 |
|---|---|---|---|---|
| GS 18 | 0.506 ± .026 | 71.51 ± .09 | 10.46 ± .02 | 17.53 ± .09 |
| 19 #1 | 1.08 ± .02 | 41.85 ± .03 | 17.28 ± .05 | 39.80 ± .02 |
| 19 #2 | 1.10 ± .01 | 39.11 ± .04 | 17.94 ± .03 | 41.86 ± .04 |
| 20 | 0.505 ± .010 | 71.86 ± .05 | 10.43 ± .03 | 17.21 ± .02 |
| 21 #1 | 0.184 ± .003 | 87.26 ± .03 | 6.77 ± .01 | 5.78 ± .02 |
| 22 | 1.36 ± .02 | 27.36 ± .03 | 20.76 ± .03 | 50.52 ± .02 |
| 23 | 0.696 ± .015 | 60.29 ± .06 | 13.36 ± .07 | 25.66 ± .06 |
| 24 | 1.36 ± .01 | 26.78 ± .02 | 20.91 ± .03 | 50.94 ± .03 |
| 28 | 1.18 ± .01 | 36.47 ± .05 | 18.72 ± .04 | 43.64 ± .05 |
| 30 | 0.768 ± .010 | 57.36 ± .05 | 13.48 ± .04 | 28.39 ± .03 |
| 31 | 0.107 ± .01 | 89.51 ± .10 | 6.86 ± .06 | 3.53 ± .07 |
| 33 | 0.082 ± .01 | 90.02 ± .02 | 6.65 ± .03 | 3.25 ± .02 |
| 34 | 0.113 ± .001 | 88.93 ± .03 | 6.88 ± .01 | 4.08 ± .02 |
| 35 #1 | 0.057 ± .003 | 92.53 ± .02 | 5.71 ± .01 | 1.70 ± .01 |
| 39 #3 | 1.09 ± .02 | 39.36 ± .02 | 17.88 ± .02 | 41.67 ± .02 |
| 40 | 0.245 ± .003 | 84.20 ± .06 | 7.51 ± .02 | 8.05 ± .05 |
| 41 | 0.223 ± .003 | 84.39 ± .05 | 7.55 ± .03 | 7.84 ± .01 |
| 42 | 0.275 ± .006 | 83.33 ± .03 | 7.90 ± .02 | 8.49 ± .02 |
| 43 | 0.042 ± .005 | 93.10 ± .03 | 5.99 ± .02 | 0.872 ± .007 |
| 47 | 0.614 ± 0.17 | 64.55 ± .08 | 12.13 ± .08 | 22.70 ± .08 |
| 48 | 0.588 ± .001 | 66.36 ± .03 | 11.68 ± .02 | 21.37 ± .04 |
| 49 | 1.30 ± .01 | 28.66 ± .03 | 20.46 ± .02 | 49.58 ± .03 |
| 50 | 0.608 ± .003 | 65.27 ± .06 | 11.90 ± .03 | 22.23 ± .05 |
| 51 | 0.900 ± .007 | 49.85 ± .02 | 15.46 ± .01 | 33.79 ± .02 |
| 63 | 0.839 ± .01 | 53.54 ± .05 | 14.74 ± .04 | 30.88 ± .04 |
| 64 | 0.154 ± .003 | 88.14 ± .03 | 6.43 ± .03 | 5.27 ± .02 |
| 65 | 0.086 ± .001 | 90.79 ± .02 | 6.28 ± .03 | 2.84 ± .03 |

| Sample | 204 | 206 | 207 | 208 |
|---|---|---|---|---|
| GS 66 | 0.257 ± .01 | 82.85 ± .12 | 8.03 ± .05 | 8.86 ± .09 |
| 67 | 1.35 ± .01 | 26.01 ± .03 | 21.03 ± .02 | 51.61 ± .05 |
| 68 | 1.36 ± .02 | 25.90 ± .03 | 21.05 ± .08 | 51.69 ± .03 |
| 70 | 1.36 ± .003 | 25.33 ± .02 | 21.12 ± .02 | 52.19 ± .05 |
| LRS 20 #2 | 0.151 ± .011 | 86.91 ± .05 | 6.79 ± .03 | 6.14 ± .04 |
| 28 #1 | 0.071 ± .007 | 92.76 ± .04 | 6.04 ± .02 | 1.13 ± .03 |
| 63 #2 | 0.176 ± .002 | 86.58 ± .03 | 7.31 ± .02 | 5.94 ± .02 |
| 64 #1 | 0.108 ± .003 | 90.25 ± .02 | 6.62 ± .02 | 3.02 ± .02 |
| Vanadinite 1/ | 1.37 | 25.20 | 21.27 | 52.17 |

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1/ Isotopic composition of lead in wulfenite and vanadinite in Nier, A. O., 1938, Variations in the relative abundances of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., vol. 60, p. 1573. The probable error in the measurements on this sample is of the order of 0.5 percent.

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