

GEOLOGICAL SURVEY CIRCULAR 271



A PRELIMINARY DETERMINATION OF  
THE AGE OF SOME URANIUM ORES  
OF THE COLORADO PLATEAUS BY  
THE LEAD-URANIUM METHOD



UNITED STATES DEPARTMENT OF THE INTERIOR  
Douglas McKay, Secretary

GEOLOGICAL SURVEY  
W. E. Wrather, Director

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

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

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## ABSTRACT

A study of the  $Pb^{206}/U$  and  $Pb^{207}/U^{235}$  ages and the  $Pb^{207}/Pb^{206}$  ratios of the uranium ores of the Colorado Plateaus was 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 per cent uranium gives an average  $Pb^{206}/U$  age of approximately 71 million years, an average  $Pb^{207}/U^{235}$  age of about 82 million years, and an average  $Pb^{207}/Pb^{206}$  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 in part 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  $\pm 3$  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.

The 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 late Cretaceous or early Tertiary (55 to 80 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 Plateaus (152 and 127 million years ago), 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 definitely 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 uranium ores of the Colorado Plateaus 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 the deposits are Late Cretaceous to early Tertiary (55 to 80 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 rocks, 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 more reliable.

This study of the age of the uranium ores of the Colorado Plateaus 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 ores of the plateaus is one of the most promising types of investigation directly related to the origin of the ore deposits in the sedimentary rocks of the plateaus. The Tertiary ages of Colorado Plateau ores published in works by Hess and Foshag (1927, p. 4), and Holmes (1931, p. 351), and the writers' 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 sedimentary rocks 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 Plateaus 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.

The writers wish to express their appreciation not only to the many members of the Survey for their

help but also to the Atomic Energy Commission's Division of Research and Division of Raw Materials for the support received. Without the isotopic analyses furnished by Dr. Roger F. Hibbs and his staff at the Mass Assay Laboratory, Carbide and Carbon Chemicals Co., 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 Co.

## SAMPLES

The sampling of the uranium deposits of the Colorado Plateaus for age studies is a specialized problem. It requires not only that the ore specimens from each of the deposits in the different mineralized stratigraphic units must be representative, but also that 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 plateaus offer little opportunity to collect specimens that will satisfy both these requirements. The compromises that 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. For this reason, the averages that are presented 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 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 shown in table 7 at the end of this report.

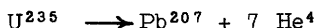
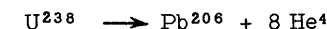
In collecting samples for this age study, an effort was made to obtain as many different types of uranium ore as possible. The uraninite specimens were collected from the Happy Jack mine, San Juan County, Utah, and the Shinarump No. 1 claim, Seven Mile Canyon, Grand County, Utah, both in the Shinarump 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, were 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) were collected from deposits in the Salt Wash sandstone member of the Morrison formation of Jurassic age. Nine mill-pulp samples representing a total of about 4,200 tons of carnotite ore from 7 different mines in the Uravan mineral belt were also studied.

## PHYSICAL CONSTANTS AND FORMULAS

The physical constants and equations used in the age calculations on the ores of the plateaus are shown below.

### *Radioactive decay schemes, physical constants, and age formulas.*

#### Decay schemes<sup>1</sup>



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

#### Physical constants

	<u><math>\lambda/\lambda U</math></u>	<u>Half-life</u>
$U^{238}$ -----	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 (after Keevil, 1939)

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

$$t = 2.37 \times 10^3 \log_{10} \left( 1 + 1.14 \frac{Pb^{207}}{U^{235}} \right)$$

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{139.0} \left( \frac{e^{\lambda_{235} t} - 1}{e^{\lambda_{238} t} - 1} \right)$$



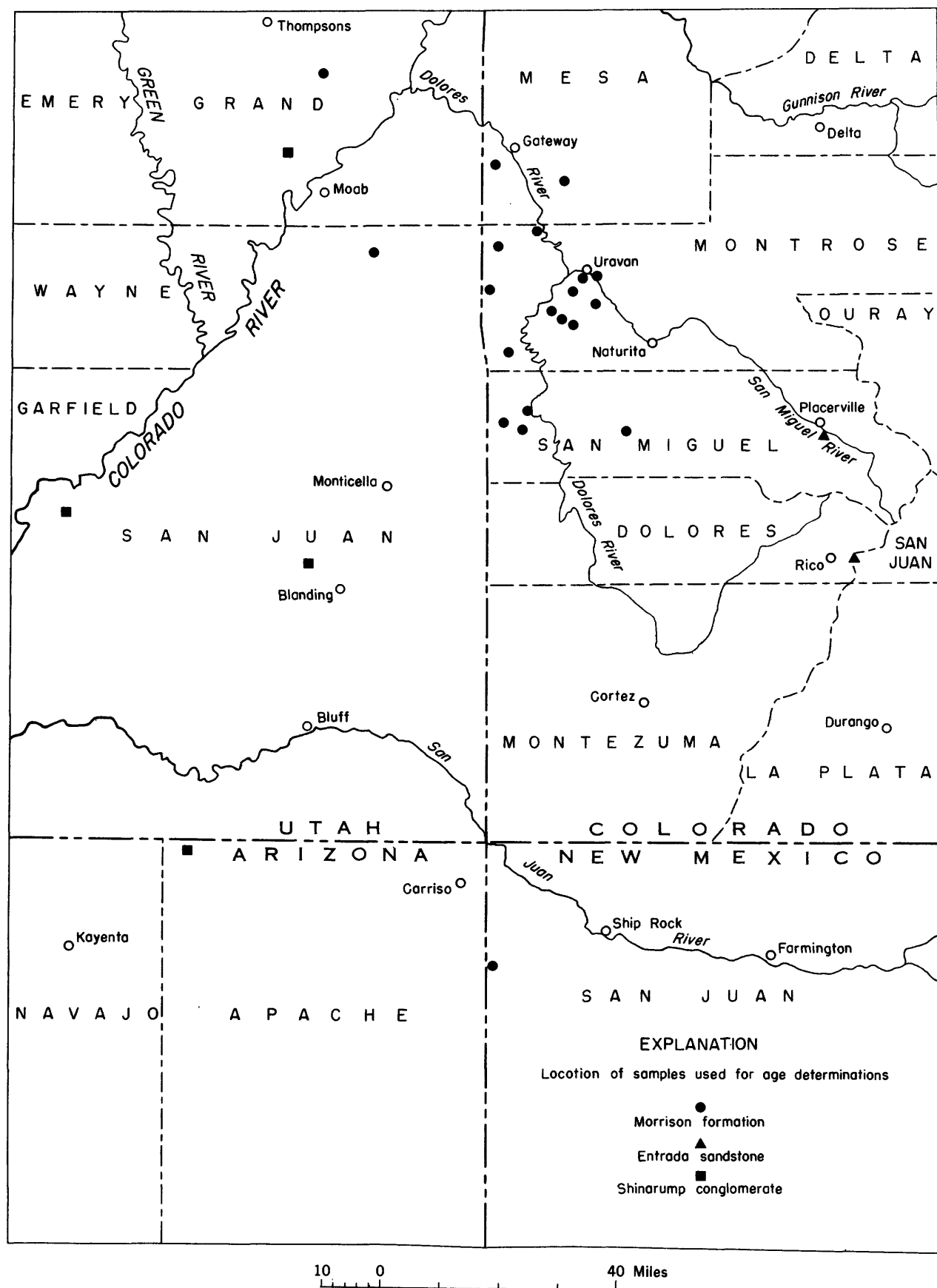


Figure 1. —Index map of part of the Colorado Plateaus showing location of samples used for age determinations.

These constants are the same as those used by Wickman (1939, p. 5)<sup>1</sup> 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 report. The most recent re-determination 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 were calculated because the correction of total U to  $U^{238}$  is much less than the chemical errors in the determination for uranium. It has been shown that the isotopic abundance of  $U^{238}$  for samples from many different sources does not differ significantly from the value 99.286 percent.

## AGE CALCULATIONS

### Corrections

The calculation of the age of the uranium ores of the plateaus 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 (or) lead due to alteration of the ore by ground waters.

Analytical errors.—All samples were carefully ground and thoroughly mixed before they were analyzed. Samples containing more than 0.1 percent uranium were analyzed volumetrically. All samples were analyzed for lead colorimetrically (Milkey, 1952, p. 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  $\pm 3$  million years. The results of the quantitative analyses of the samples used for age determinations are given in table 8, p. 18.

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. Known systematic mass spectrometric errors probably 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 table 9, p. 19.

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, previously unrecognized systematic mass spectrometric errors.

The additional systematic error in the  $Pb^{204}/Pb^{208}$  ratios of the radiogenic leads may 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  $Pb^{204}$ ,  $Pb^{207}$ , and  $Pb^{208}$  slightly higher than their true values, abundances of  $Pb^{208}$  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 leads of the Colorado Plateaus (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 ores of the plateaus with the common leads of the plateaus 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, reliable  $Pb^{207}/Pb^{206}$  ages for the uranium ores of the Colorado Plateaus cannot be made. For this reason  $Pb^{207}/Pb^{206}$  ages are not 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, are presented.

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 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 probable 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).

<sup>1</sup>See page 16 for literature cited.

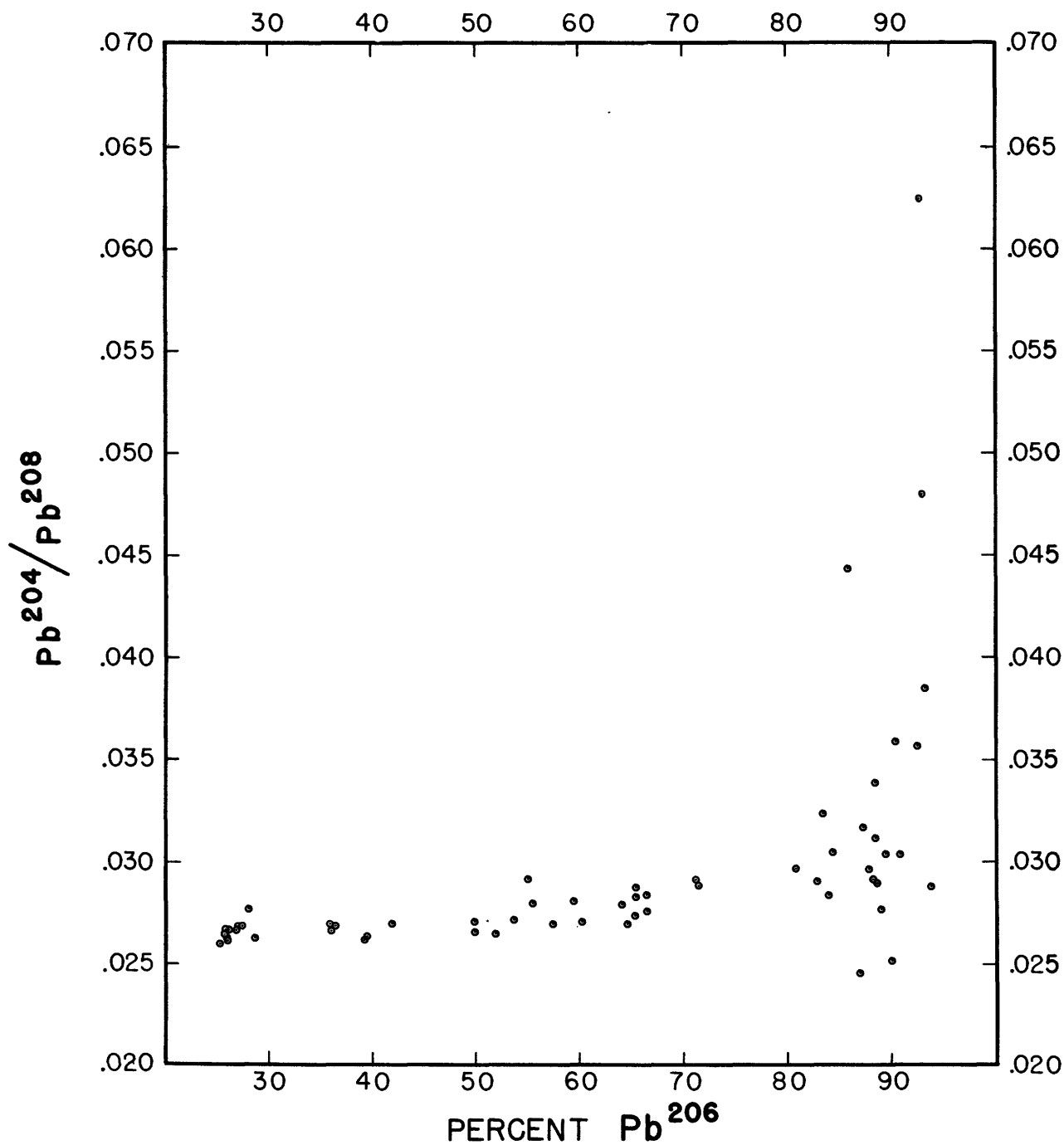


Figure 2. —The effect of increased  $Pb^{206}$  on  $Pb^{204}/Pb^{208}$ .

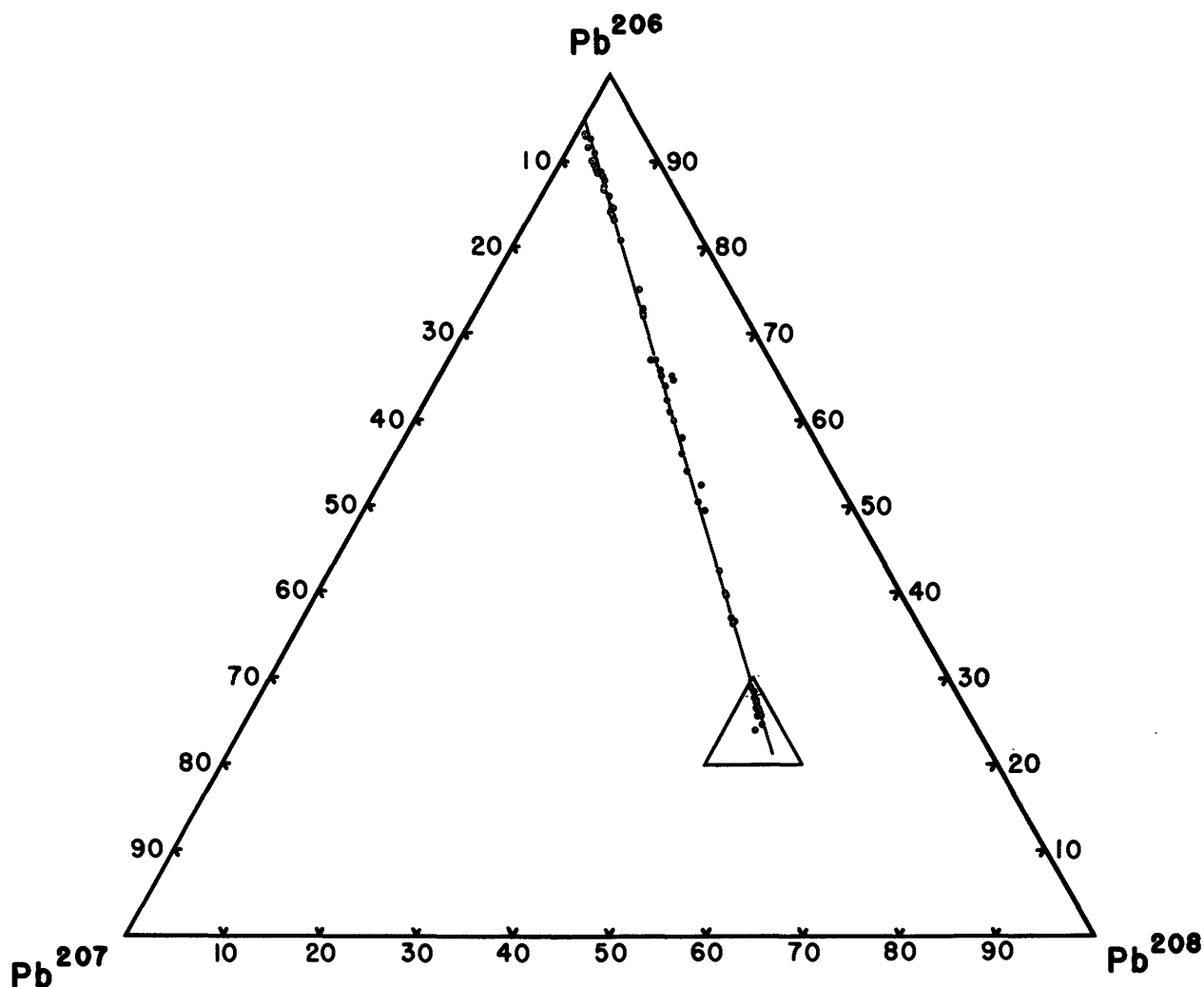


Figure 3. —Triangular diagram of lead isotopes.

The quantitative effects of common lead corrections on the lead-uranium and lead-lead ages are a function of the  $\text{Pb}^{206}/\text{U}$ ,  $\text{Pb}^{207}/\text{U}^{235}$ , and  $\text{Pb}^{207}/\text{Pb}^{206}$  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  $\text{Pb}^{207}/\text{Pb}^{206}$  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 Plateaus that contain large amounts 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 the vanadinite from the Tucson Mountains of Miocene age is on the composition line of the uranium and vanadium ores of the Colorado Plateaus apparently of early Tertiary(?) age, although the similarities in isotopic composition certainly suggest that all these samples are in some way genetically related. In any event, the composition of this lead from the Tucson Mountains was chosen for many of the age calculations because this lead contains less uranium lead than any other which could legitimately be considered. This lead, therefore, will give the greatest  $\text{Pb}^{206}/\text{U}$  ages when used in the common-lead correction.

In contrast to the variable  $\text{Pb}^{204}/\text{Pb}^{208}$  ratio for the ores containing large amounts of radiogenic lead,

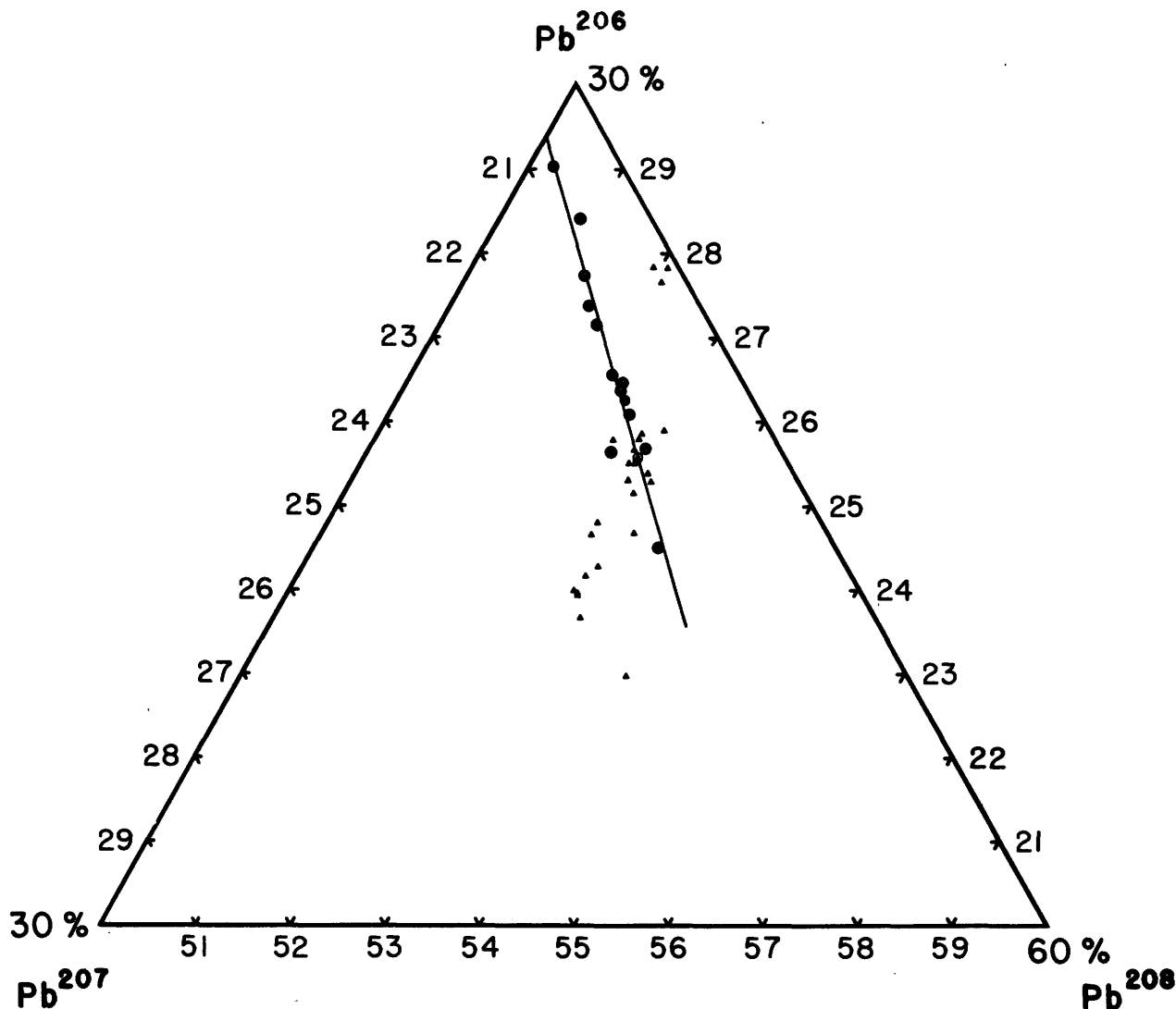


Figure 4. —Triangular diagram of common leads.

the  $Pb^{204}/Pb^{208}$  ratio of the common leads from the Colorado Plateaus is almost constant and is approximately 0.02651. The relatively uniform  $Pb^{204}/Pb^{208}$  ratio of these common leads is due to the absence of thorium, even in very small amounts, in the ore, and to the relatively low abundance of  $Pb^{208}$  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. However, in calculating the ages of the ores of the Colorado Plateaus,  $Pb^{208}$  was used for the three following reasons:

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 ( $Th^{232}$ ).

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

The use of the  $Pb^{206}$  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 ores of the plateaus.

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 were analyzed by Nier (1938, p. 1573; Nier, Thompson, and Murphey, 1941, p. 115) were 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 be more than 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 p. 2.) Because of the uncertainty of the exact values for the radiogenic  $Pb^{207}/Pb^{206}$  ratios, no detailed correction for loss of radon was made. A maximum, although improbable, correction for loss of radon would increase the mean  $Pb^{206}/U$  age 10 million years, but the mean  $Pb^{207}/U^{238}$  age would remain unchanged.

Loss of uranium.—It is the belief of the writers 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 leaching by ground water of uranium rather than 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 were not made for the possible loss of uranium because of the difficulty of determining this factor quantitatively. There is abundant evidence on the plateaus, however, of the alteration and leaching of the ore bodies by surface and ground waters. Therefore, the mean  $Pb^{206}/U$  ages that were calculated are probably older than the actual ages of the specimens.

Our data confirm the fact discussed by Ellsworth (1932, p. 423) and Nier (1939b, p. 159) 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 were 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 plateaus 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 uranium deposits of the Colorado Plateaus 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. Ores of different grade, mineralogic composition, and uranium distribution from the plateaus will be studied in the laboratory by leaching with weakly alkaline solutions.

Many of the events in the geochemical history of the uranium deposits of the plateaus, 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  $U^{238}/Pb^{208}$  (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  $Pb^{207}/Pb^{208}$  ages and whether old radiogenic lead was added to the ores at the time of their deposition.

#### CALCULATED AGES

##### $Pb^{206}/U$ ages of 41 uranium ores of the Colorado Plateaus

It is true, not only for the uranium ores of the Colorado Plateaus but also for any large group of samples used for lead-uranium age studies, that all the specimens will not give equally reliable ages. The best materials are those which are unaltered and which have a high  $UO_2$  content. As previously mentioned, in this preliminary determination of the age of the uranium in the ores of the plateaus, 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 41 samples studied is that the averages which are given below are probably higher than the actual age of the ore.

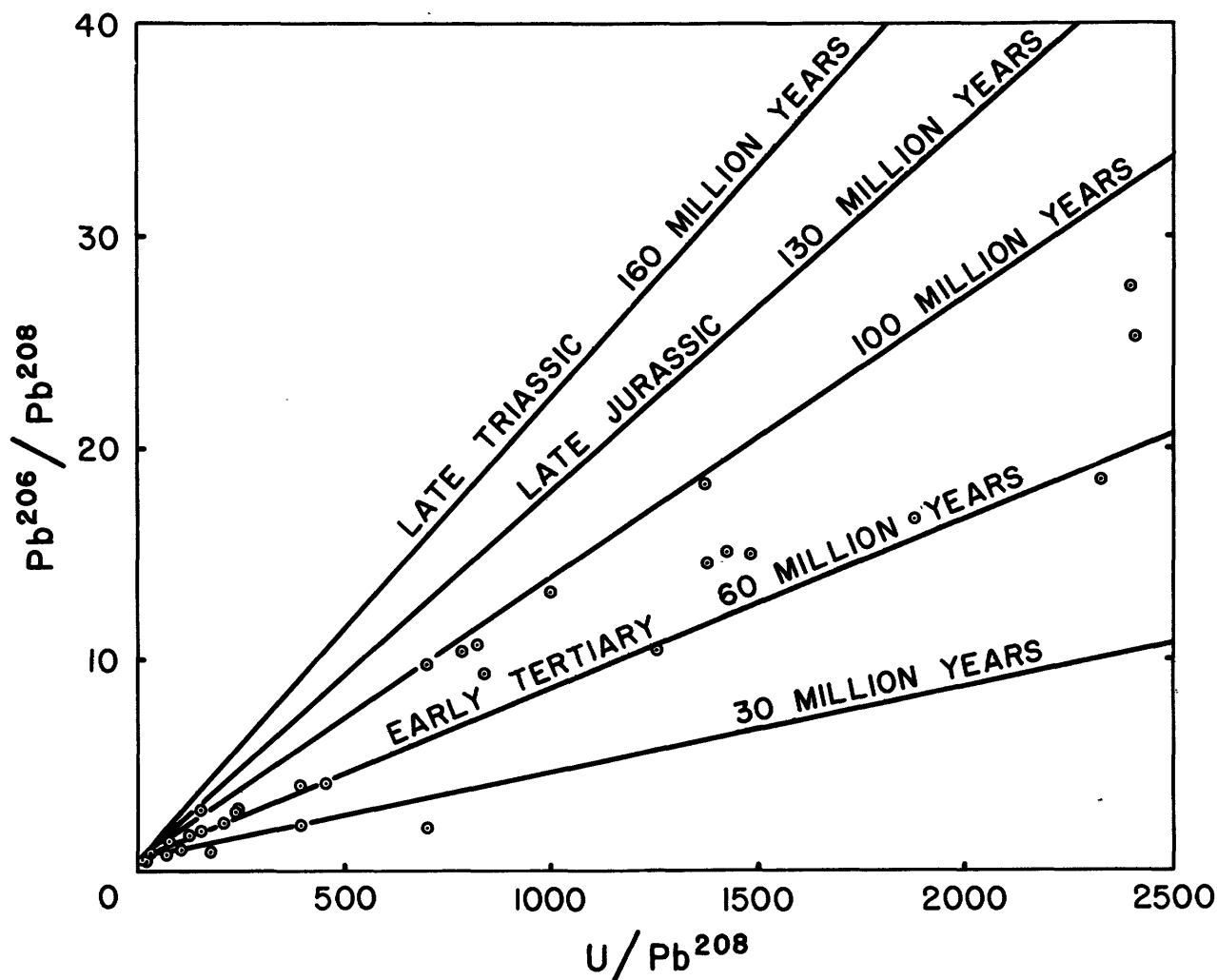


Figure 5.  $\text{Pb}^{206}/\text{Pb}^{208}$  as a function of  $\text{U}/\text{Pb}^{208}$ .

A histogram (fig. 7) of the corrected  $\text{Pb}^{206}/\text{U}$  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 tables 1 and 2 (see p. 12) 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 1) 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 lead mineral nearest the deposit (best) from which the ore sample was taken. The wide range for both total lead and total  $\text{Pb}^{206}$  ages is shown by the fact that the mean age is greater than the third quartile.

#### $\text{Pb}^{207}/\text{U}^{235}$ ages of 41 uranium ores of the Colorado Plateaus

Most of the  $\text{Pb}^{207}/\text{U}^{235}$  ages (table 2, p. 12) are greater than the  $\text{Pb}^{206}/\text{U}$  ages because the systematic mass spectrometric errors result in apparent  $\text{Pb}^{207}$  abundances which are greater than the actual abundances of this isotope. The total  $\text{Pb}^{207}/\text{U}^{235}$  age is greater than the total  $\text{Pb}/\text{U}$  age because samples

containing large amounts of common lead contain a greater percentage of  $\text{Pb}^{207}$  than do samples of pure radiogenic lead. The similarity of the mean (best) lead and vanadinite  $\text{Pb}^{207}/\text{U}^{235}$  ages reflects the relatively small variations that have been found in the  $\text{Pb}^{207}/\text{Pb}^{208}$  ratios of the common leads of the plateaus.

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

The tabulation of the samples according to grade (table 3, p. 12) shows a small difference in mean  $\text{Pb}^{206}/\text{U}$  ages. Generally the lower grade uranium ores contain relatively larger amounts of common lead. The  $\text{Pb}^{206}/\text{U}$  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.

The lower  $\text{Pb}^{207}/\text{Pb}^{206}$  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  $\text{Pb}^{204}$ ,  $\text{Pb}^{207}$ , and  $\text{Pb}^{208}$  peaks

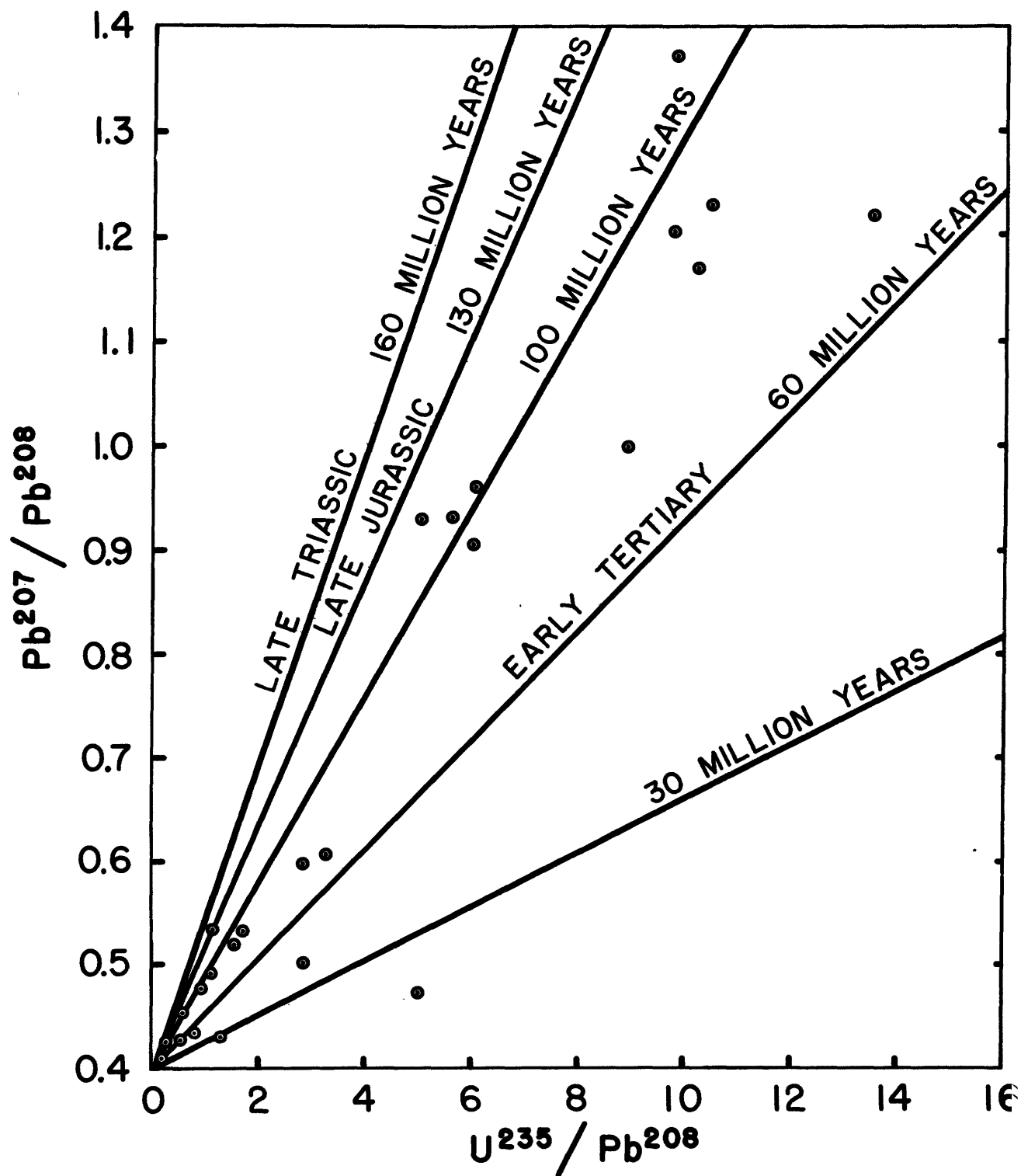


Figure 6.  $-Pb^{207}/Pb^{208}$  as a function of  $U^{235}/Pb^{208}$ .



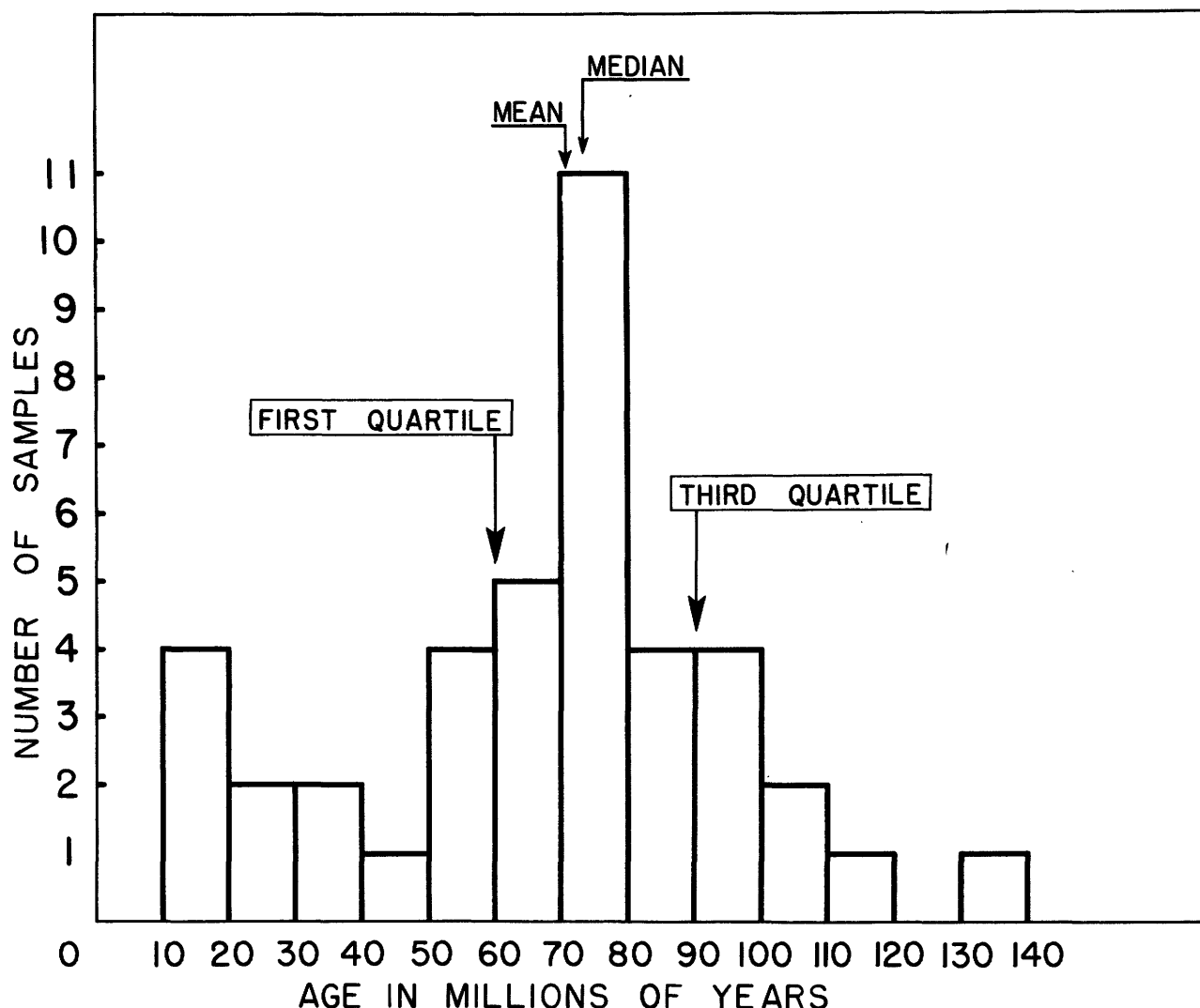


Figure 7. —Histogram of results of age calculations.

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 4, p. 14). The mill-pulp samples were obtained from the ore-sampling plants of the U. S. Vanadium Co. Each sample is a split from about 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.

The greater age of the ores that 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 lost less radon and (or) received less old radiogenic lead.

Table 1.—Pb/U and Pb<sup>206</sup>/U ages of 41 uranium ores of the Colorado Plateaus

[In millions of years]

	Mean	1st quartile	Median	3d quartile
Total Pb/U-----	270	77.5	110	165
Total Pb <sup>206</sup> /U-----	120	67.5	85	105
Radiogenic Pb <sup>206</sup> /U (vanadinite) <sup>1</sup> -----	71	60	75	90
Radiogenic Pb <sup>206</sup> /U (best)-----	68	60	75	90

<sup>1</sup>The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.Table 2.—Total and corrected Pb<sup>207</sup>/U<sup>235</sup> ages of 41 uranium ores of the Colorado Plateaus

[In millions of years]

	Mean	1st quartile	Median	3d quartile
Total Pb <sup>207</sup> /U <sup>235</sup> <sup>1</sup> -----	429	119	168	339
Radiogenic Pb <sup>207</sup> /U <sup>235</sup> (vanadinite) <sup>2</sup> -----	82	66.8	86.9	103.2
Radiogenic Pb <sup>207</sup> /U <sup>235</sup> (best)-----	82	66.5	88.6	103.7

<sup>1</sup>Data on 40 samples.<sup>2</sup>The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.Table 3.—Pb<sup>206</sup>/U ages and Pb<sup>207</sup>/Pb<sup>206</sup> ratios of 41 uranium ore samples of the Colorado Plateaus grouped by grade of sample

Grade of sample (percent uranium)	Number of samples	Mean Pb <sup>206</sup> /U age in millions of years <sup>1</sup>	Mean Pb <sup>207</sup> /Pb <sup>206</sup> ratio
>10 -----	16	68	0.0576
1.0-10.0 -----	8	70	.0568
0.1- 1.0 -----	17	75	.0533

<sup>1</sup>The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.

Pb<sup>206</sup>/U ages and Pb<sup>207</sup>/Pb<sup>206</sup> ratios of samples  
grouped by stratigraphic position

The mean Pb<sup>206</sup>/U ages of the samples tabulated according to the stratigraphic unit in which the deposits are found (table 5, p. 14) does not show any correlation with the age of the enclosing sediments. In spite of the uncertainty concerning the Pb<sup>207</sup>/Pb<sup>206</sup> 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<sup>207</sup>/Pb<sup>206</sup> ratio of the ores of the Morrison and Shinarump suggests that the ores in both formations were deposited at the same time and (or) came from similar sources at depth.

The Pb<sup>206</sup>/U and Pb<sup>207</sup>/Pb<sup>206</sup> ratios of ores from the Entrada sandstone are not very reliable because 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<sup>207</sup>/Pb<sup>206</sup> ratios for 2 of the 3 samples.

An unsuspected relation between the deposits of argentiferous galena in the Pony Express limestone member of the Wanakah formation and the underlying uranium-bearing "roscoelite" ores in the Entrada sandstone 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 (table 9, sample GS 5, p. 19) is bracketed by the composition of the leads from the ores of the Bear Creek mine and adjacent Primus claim (table 9, samples GS 22 and 24, p. 19). 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<sup>206</sup>/U ages and Pb<sup>207</sup>/Pb<sup>206</sup> 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 6. (See p. 14.)

The Pb<sup>206</sup>/U ages of the carnotite ores range from 20 to 140 million years. From the field relations of individual samples as well as their chemistry, the writers 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 partly 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 gives a Pb<sup>207</sup>/U age of 80 million years, and a black ore containing an undescribed uranium mineral from La Sal No. 2 mine gives a Pb<sup>206</sup>/U age of 90 million years.

The writers believe that the age determinations which were made on the Happy Jack and Shinarump No. 1 uraninite specimens, 65 and 75 million years (Stieff and Stern, 1952, p. 707), are the most reliable that have been made on the uranium ores of the Colorado Plateaus. The mean Pb<sup>206</sup>/U age of 70 million years for the two uraninite samples of the Shinarump conglomerate 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<sup>207</sup>/Pb<sup>206</sup> 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<sup>206</sup>/U<sup>236</sup> ages for the end of the Triassic and Jurassic are not available, the beginning of the Tertiary has been dated by Holmes (1946a, p. 145) who recalculated the Pb<sup>206</sup>/U<sup>236</sup> age of two Colorado Front Range pitchblendes as 57.3 and 59.8 million years. Two additional Front Range pitchblendes which were analyzed in the Geological Survey laboratory give Pb<sup>206</sup>/U ages of 60 and 70 million years. The average age of the uraninite samples from the Shinarump conglomerate is 70 million years, and both these samples show slightly high Pb<sup>207</sup>/Pb<sup>206</sup> ratios. If old radiogenic lead is partly responsible for the high Pb<sup>207</sup>/Pb<sup>206</sup> ratios, the true ages of the Shinarump uraninites would probably be somewhat less than 65 million years. The similarity in age of the pitchblendes from sedimentary rocks in the Colorado Plateaus and in the vein deposits in the Colorado Front Range is striking.

## SUMMARY AND CONCLUSIONS

The calculation of the age of the uranium ores of the Colorado Plateaus 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<sup>206</sup>/U age of approximately  $\pm 3$  million years. However, the mean lead-uranium ages presented are given without limits because of the inability of the writers at this time to evaluate quantitatively several of the remaining corrections. These ages, therefore, were calculated so that any changes in them due to more probable common lead corrections, to the presence of old radiogenic lead, or to loss of uranium will only lower the mean age. The systematic mass spectrometric errors should not increase the mean Pb<sup>206</sup>/U age by more than 3 million years. An increase of approximately 10 million years in the mean Pb<sup>206</sup>/U age can be expected only if radon loss is demonstrated to have been

Table 4.— $Pb^{206}/U$  ages and  $Pb^{207}/Pb^{206}$  ratios of 41 uranium ore samples of the Colorado Plateaus grouped by type of sample

Type of sample	Number of samples	Mean $Pb^{206}/U$ age in millions of years <sup>1</sup>	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	.0566

<sup>1</sup> The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.

Table 5.— $Pb^{206}/U$  ages and  $Pb^{207}/Pb^{206}$  ratios of 41 uranium ore samples of the Colorado Plateaus grouped by stratigraphic position

Formation	Age of stratigraphic unit in millions of years <sup>1</sup>	Number of samples	Mean $Pb^{206}/U$ age in millions of years <sup>2</sup>	Mean $Pb^{207}/Pb^{206}$ ratio
Morrison formation-----	127	34	72	0.0550
Entrada sandstone-----	130-140	3	50	<sup>3</sup> .0627
Shinarump conglomerate-----	152	4	73	.0548

<sup>1</sup> Holmes, 1946 a, p. 145.

<sup>2</sup> Isotopic composition of the lead in vanadinite used to correct for common lead present. Analysis in Nier, 1938.

<sup>3</sup> 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.

Table 6.— $Pb^{206}/U$  ages and  $Pb^{207}/Pb^{206}$  ratios of 41 uranium ore samples of the Colorado Plateaus grouped by mineralogic composition

Mineralogic composition	Number of samples	Mean $Pb^{206}/U$ age in millions of years <sup>1</sup>	Mean $Pb^{207}/Pb^{206}$ ratio
Carnotite-----	34	72	0.0552
Vanadiferous hydromica-----	3	50	<sup>2</sup> .0627
Undescribed uranium minerals-----	2	85	.0568
Uraninite-----	2	70	.0530

<sup>1</sup> The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.

<sup>2</sup> 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.

a major process on the plateaus 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 the common leads of the plateaus with Nier's 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 common leads of the plateaus that were 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 are not presented in this report, the partly corrected but still anomalous  $Pb^{207}/Pb^{206}$  ratios are 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 are 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 deposits of the plateaus 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 sedimentary rocks of Late Triassic and Late Jurassic age. These rocks are thought to differ in age by about 30 million years, and the Late Jurassic rocks are believed to be about 130 million years old. The absence of any correlation between the age of the enclosing sedimentary rock 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, are the most reliable that we have made on any uranium ore of the plateaus. Of the 2, 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 probably correct within approximately 5 million years. The age of the enclosing Late Triassic rocks, about 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 4 early Tertiary Colorado Front Range pitchblende samples, 2 analyzed by Nier and 2 determined in the Geological Survey laboratory.

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

1. Uranium was deposited either at the same time or shortly after the enclosing Jurassic and Triassic sedimentary rocks 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 that had been formed were taken into solution, and the uranium was eventually redeposited in about its present sites. The deficiency of radiogenic lead for a syngenetic ore indicates that most of the radiogenic lead formed before 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 before 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 plateaus. 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 uranium ores of the Colorado Plateaus was to determine whether these ores were deposited during the Triassic and Jurassic periods or whether all 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 the writers' 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 these uranium deposits, it is certain that the conditions prevailing during the close of the Cretaceous and the beginning of the Tertiary must have had 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 so clear, but perhaps the present reexamination 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 sandstone member of the Morrison formation below the present "ore zone." If the ore solutions were introduced from below, it is possible that the potentialities of the Colorado Plateaus as a uraniferous province have merely been touched.

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Table 7.—Uranium ores of the Colorado Plateaus used for age calculations<sup>1</sup>

Sample no.	Location	Mineralogic composition	Pb <sup>206</sup> /U age in millions of years <sup>2</sup>	Corrected Pb <sup>207</sup> /Pb <sup>206</sup>
Shinarump conglomerate				
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-----	-----do-----	65	.0501
GS 13	Monument No. 2 mine, Apache County, Ariz.-	Carnotite type---	75	.0570
GS 66	Camp Bird No. 13 mine, Temple Mountain, Emery County, Utah.	Asphaltic type---	80	.0560
Entrada sandstone <sup>3</sup>				
GS 22	Bear Creek mine, San Miguel County, near Placerville, Colo.	Vanadiferous hydromica.	20	.0578
GS 28	Vanadous No. 1 mine, San Miguel County, Colo.	-----do-----	40	.0603
GS 24	Primus claim, San Miguel County, Colo.---	-----do-----	90	.0692
Morrison formation				
GS 20	Roc Creek mine, Montrose County, Colo.---	Carnotite type---	60	.0537
GS 65	La Sal No. 2 mine, Mesa County, Colo.---	New uranium-vanadium mineral.	90	.0570
GS 21	Calamity No. 13 mine, Mesa County, Colo.--	Carnotite type---	75	.0523
GS 31	-----do-----	-----do-----	75	.0617
GS 33	-----do-----	-----do-----	85	.0601
GS 34	-----do-----	-----do-----	75	.0599
GS 35	-----do-----	-----do-----	105	.0547
GS 42 <sup>4</sup>	-----do-----	-----do-----	100	.0560
GS 43	-----do-----	-----do-----	140	.0608
GS 10	-----do-----	-----do-----	70	.0610
LRS 28	-----do-----	-----do-----	75	.0605
GS 41 <sup>4</sup>	Calamity No. 21 mine, Mesa County, Colo.--	-----do-----	90	.0541
GS 40 <sup>4</sup>	Calamity No. 27 mine, Mesa County, Colo.--	-----do-----	95	.0526
LRS 63--2	Club mine, Montrose County, Colo.---	-----do-----	75	.0584
GS 11	-----do-----	-----do-----	60	.0593
GS 12	-----do-----	-----do-----	70	.0582
GS 48 <sup>4</sup>	Mill No. 1 mine, Montrose County, Colo.---	-----do-----	85	.0531
GS 30	Rock Raven No. 3 mine, Montrose County, Colo.	-----do-----	15	.0437
GS 47 <sup>4</sup>	Colordadium mine, Montrose County, Colo.---	-----do-----	75	.0537
GS 39--3 <sup>4</sup>	Long Park No. 10 mine, Montrose County, Colo.	-----do-----	110	.0467
GS 18	Bitter Creek mine, Montrose County, Colo.---	-----do-----	70	.0525
GS 15--1	Jo Dandy mine, Montrose County, Colo.---	-----do-----	20	.0653
GS 15--2	-----do-----	-----do-----	60	.0594
GS 19--1	Wild Steer mine, Montrose County, Colo.---	-----do-----	40	.0466
GS 19--2	-----do-----	-----do-----	20	.0464
LRS 64--1	Bob Tail mine, Montrose County, Colo.---	-----do-----	30	.0607
GS 49 <sup>4</sup>	Red Bird mine, Montrose County, Colo.---	-----do-----	75	.0518
GS 14	Mine D mine, Montrose County, Colo.---	-----do-----	100	.0543
GS 17	Butterfly mine, Montrose County, Colo.---	-----do-----	35	.0542
GS 23	Raven mine, Montrose County Colo.---	-----do-----	70	.0605
GS 50 <sup>4</sup>	Charles T No. 2 mine, San Miguel County, Colo.	-----do-----	120	.0521
GS 16	Radium No. 6 mine, San Miguel County, Colo.	-----do-----	60	.0530
LRS 20--2	-----do-----	-----do-----	30	.0511
GS 51 <sup>4</sup>	Radium No. 8 mine, San Miguel County, Colo.	-----do-----	100	.0502

See footnotes at the end of the table.

Table 7.—Uranium ores of the Colorado Plateaus used for age calculations<sup>1</sup>—Continued

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

<sup>1</sup>The isotopic composition of the lead in vanadinite was used to correct for common lead present. Analysis in Nier, 1938.

<sup>2</sup>Age expressed to nearest 5 million years.

<sup>3</sup>The Pb<sup>207</sup>/Pb<sup>206</sup> 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.

<sup>4</sup>Mill pulp sample.

Table 8.—Lead and uranium content of uranium ores used for age calculations

[Analysts, R. G. Milkey, Harry Levine, and Frank Cuttitta, U. S. Geological Survey]

Sample no.	g Pb/g sample	g U/g sample	Sample no.	g Pb/g sample	g U/g sample
GS 10	0.0033	0.325	GS 34	0.000254	0.0228
11	.0032	.322	35—1	.000313	.0209
12	.0033	.148	39—3	.000155	.0021
13	.00183	.1554	40	.000068	.0043
14	.00176	.1168	41	.000074	.0049
15—1	.0008	.311	42	.000052	.0031
15—2	.00166	.1910	43	.0047	.241
16	.00128	.1443	47	.000062	.0033
17	.000705	.0740	48	.000089	.0046
18	.000052	.0036	49	.00057	.0027
19—1	.0011	.0463	50	.000052	.0018
19—2	.000116	.0086	51	.000132	.0034
20	.000060	.0047	63	.0143	.559
21—1	.000093	.0077	64	.0074	.7346
22	.000552	.0064	65	.0014	.102
23	.00062	.0341	66	.00039	.0290
24	.00118	.0022			
28	.000102	.0031	LRS 20—2	.0015	.326
30	.000023	.0046	28—1	.0038	.360
31	.000300	.0256	63—2	.0031	.254
33	.000402	.0314	64—1	.0014	.346



Table 9.—Isotopic composition of lead from uranium ores and lead minerals of the Colorado Plateaus

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

Sample	Atom percent abundance of lead isotopes <sup>1</sup>			
	204	206	207	208
GS 1-----	1.38 ± .01	26.10 ± .05	20.97 ± .02	51.55 ± .05
GS 2-----	1.37 ± .03	26.07 ± .05	21.00 ± .03	51.56 ± .08
GS 5-----	1.363 ± .008	27.00 ± .05	20.86 ± .03	50.77 ± .05
GS 6-----	1.40 ± .01	25.29 ± .04	21.48 ± .03	51.84 ± .04
GS 7-1-----	1.37 ± .02	25.73 ± .08	21.09 ± .09	51.81 ± .02
GS 7-2-----	1.36 ± .02	25.78 ± .05	20.97 ± .18	51.90 ± .07
GS 8-----	1.39 ± .05	28.02 ± .08	20.45 ± .04	50.14 ± .05
GS 9-1-----	1.38 ± .01	26.20 ± .03	21.02 ± .02	51.41 ± .04
GS 9-2-----	1.38 ± .01	26.20 ± .03	21.06 ± .03	51.36 ± .04
GS 10-----	.029 ± .003	92.92 ± .05	6.05 ± .07	1.00 ± .02
GS 11-----	.227 ± .004	83.76 ± .03	8.00 ± .02	8.01 ± .02
GS 12-----	.820 ± .013	55.57 ± .08	14.34 ± .03	29.27 ± .10
GS 13-----	.169 ± .012	86.87 ± .02	7.16 ± .04	5.80 ± .02
GS 14-----	.150 ± .003	88.40 ± .03	6.64 ± .02	4.82 ± .02
GS 15-1-----	.159 ± .009	91.40 ± .03	6.64 ± .03	1.80 ± .01
GS 15-2-----	.034 ± .003	93.23 ± .01	5.87 ± .02	.871 ± .013
GS 16-----	.138 ± .003	88.59 ± .02	6.51 ± .02	4.76 ± .02
GS 17-----	.746 ± .008	59.41 ± .11	13.35 ± .06	26.50 ± .09
GS 18-----	.506 ± .026	71.51 ± .09	10.46 ± .02	17.53 ± .09
GS 19-1-----	1.08 ± .02	41.85 ± .03	17.28 ± .05	39.80 ± .02
GS 19-2-----	1.10 ± .01	39.11 ± .04	17.94 ± .03	41.86 ± .04
GS 20-----	.505 ± .010	71.86 ± .05	10.43 ± .03	17.21 ± .02
GS 21-1-----	.184 ± .003	87.26 ± .03	6.77 ± .01	5.78 ± .02
GS 22-----	1.36 ± .02	27.36 ± .03	20.76 ± .03	50.52 ± .02
GS 23-----	.696 ± .015	60.29 ± .06	13.36 ± .07	25.66 ± .06
GS 24-----	1.36 ± .01	26.78 ± .02	20.91 ± .03	50.94 ± .03
GS 28-----	1.18 ± .01	36.47 ± .05	18.72 ± .04	43.64 ± .05
GS 30-----	.768 ± .010	57.36 ± .05	13.48 ± .04	28.39 ± .03
GS 31-----	.107 ± .01	89.51 ± .10	6.86 ± .06	3.53 ± .07
GS 33-----	.082 ± .01	90.02 ± .02	6.65 ± .03	3.25 ± .02
GS 34-----	.113 ± .001	88.93 ± .03	6.88 ± .01	4.08 ± .02
GS 35-1-----	.057 ± .003	92.53 ± .02	5.71 ± .01	1.70 ± .01
GS 39-3-----	1.09 ± .02	39.36 ± .02	17.88 ± .02	41.67 ± .02
GS 40-----	.245 ± .003	84.20 ± .06	7.51 ± .02	8.05 ± .05
GS 41-----	.223 ± .003	84.39 ± .05	7.55 ± .03	7.84 ± .01
GS 42-----	.275 ± .006	83.33 ± .03	7.90 ± .02	8.49 ± .02
GS 43-----	.042 ± .005	93.10 ± .03	5.99 ± .02	.872 ± .007
GS 47-----	.614 ± .17	64.55 ± .08	12.13 ± .08	22.70 ± .08
GS 48-----	.588 ± .001	66.36 ± .03	11.68 ± .02	21.37 ± .04
GS 49-----	1.30 ± .01	28.66 ± .03	20.46 ± .02	49.58 ± .03
GS 50-----	.608 ± .003	65.27 ± .06	11.90 ± .03	22.23 ± .05
GS 51-----	.900 ± .007	49.85 ± .02	15.46 ± .01	33.79 ± .02
GS 63-----	.839 ± .01	53.54 ± .05	14.74 ± .04	30.88 ± .04
GS 64-----	.154 ± .003	88.14 ± .03	6.43 ± .03	5.27 ± .02
GS 65-----	.086 ± .001	90.79 ± .02	6.28 ± .03	2.84 ± .03
GS 66-----	.257 ± .01	82.85 ± .12	8.03 ± .05	8.86 ± .09
GS 67-----	1.35 ± .01	26.01 ± .03	21.03 ± .02	51.61 ± .05
GS 68-----	1.36 ± .02	25.90 ± .03	21.05 ± .08	51.69 ± .03
GS 70-----	1.36 ± .003	25.33 ± .02	21.12 ± .02	52.19 ± .05
LRS 20-2-----	.151 ± .011	86.91 ± .05	6.79 ± .03	6.14 ± .04
LRS 28-1-----	.071 ± .007	92.76 ± .04	6.04 ± .02	1.13 ± .03
LRS 63-2-----	.176 ± .002	86.58 ± .03	7.31 ± .02	5.94 ± .02
LRS 64-1-----	.108 ± .003	90.25 ± .02	6.62 ± .02	3.02 ± .02
Vanadinite <sup>2</sup> -----	1.37	25.20	21.27	52.17

<sup>1</sup>The limits of precision are calculated so that 95 percent of any new determination will fall within the limits given.<sup>2</sup>Isotopic composition of lead in wulfenite and vanadinite in Nier, 1938. The probable error in the measurements on this sample is of the order of 0.5 percent.

