Reports

Lead Isotopes and the Age of the Earth

Abstract. *Calculations based on comparison of the isotopic composition of lead from iron meteorites with that of various modern terrestrial leads have placed the age of the earth at around 4550 million years. However, recent data from young volcanic rocks reveal that modern terrestrial lead can have a wide range in isotopic composition. The variations in its composition mean that one or more of the assumptions used in the age calculation have been violated. We modified the usual approach by comparing meteorite lead with lead from rocks 2700 million years old, from the Canadian Shield. Using this method and the same constants and assumptions utilized in the earlier calculations we calculated an age of 4750 ± 50 million years for the earth. The earth may be approximately 200 million years older than previously thought; alternatively, primordial terrestrial lead may not have had the same isotopic composition as lead in iron meteorites does.*

Calculations of the age of the earth are based on an attempt to determine when terrestrial lead had the same isotopic composition as does lead observed today in the troilite phase of certain iron meteorites. The ratio of uranium to lead in the troilite phase is so low that the decay of the uranium in the mineral would not have changed isotopic composition of lead measurably over many billions of years. On the other hand readily measurable increments of radiogenic lead have been produced over the past several billion years in the outer portions of the earth that we can sample and study. With this knowledge, an age for the earth can be calculated under the following assumptions: (i) The isotopic composition of terrestrial lead at the time of formation of the earth was identical to that in meteoritic troilite. (ii) The uranium-lead ratios in the outer portion of the earth were established in a short time, relative to the age of the earth. (iii) These systems have been chemically closed with respect to uranium and lead since they were established—that is, changes in the concentrations of these elements have been due solely to radioactive decay. The difference between the isotopic composition of troilite lead and that of terrestrial lead determines the increments of radiogenic Pb^{206} and radiogenic Pb^{207} in the terrestrial lead, and these increments determine an age for the earth according to the equation

$$\frac{b - b_0}{a - a_0} = \frac{R\,(e^{\lambda' t} - 1)}{(e^{\lambda t} - 1)}$$

where a and b are the Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios for present-day terrestrial lead; a_0 and b_0 are the same ratios for troilite lead; R is the present ratio of U^{235}/U^{238}; λ' is the decay constant for U^{235}; λ is the decay constant for U^{238}; and t is the age of the earth. The method is analogous to that used to determine the Pb^{207}-Pb^{206} age of a mineral, when the correction for primary lead is usually inferred from measurement of the isotopic composition of lead from presumed cogenetic potassium feldspar or galena.

Several authors have used this method with isotopic values for meteorite and modern terrestrial lead from various sources and have found ages of around 4550 million years for the earth (*1*). Lead from young volcanic rocks, particularly basalts, and lead ores have been used to determine the isotopic composition of modern terrestrial lead. Since the isotopic composition of lead in surface rocks is in general quite variable, basic volcanic rocks, which are believed to originate in the outer mantle or lower crust of the earth, seem the most likely of any rocks that can be obtained to contain lead fulfilling the closed-system requirement. Volcanic rocks from the ocean basins are especially promising as the earth's crust is thin in such areas, and contamination with crustal lead is much less likely to occur here than on continents.

Recent papers (*2*, *3*) on the isotopic composition of lead in young volcanic rocks from the ocean basins show that the lead from these rocks is of variable isotopic composition. Values for the age of the earth which vary from 4420 to 4650 million years can be calculated from these data. Obviously some, if not all, of the rocks contain lead whose history does not fulfill the three assumptions stated above. Close study of the data shows that the closed-system requirement has been violated (*2*). Variations in the isotopic composition of lead in the basalts show that the uranium-lead ratios in the source materials have differred greatly during the past billion years or so. Possibly other assumptions have been violated as well.

Since the closed-system assumption does not hold for lead in young rocks, study of the isotopic composition of lead in the oldest rocks that can be obtained seems desirable. The error introduced into the age calculation by the failure of the closed-system assumption should be less when older rocks are used, providing their age and the isotopic composition of lead in the rocks at the time of crystallization can be accurately determined. In making such a study it is necessary to utilize lead from granitic rocks and galena ore bodies since basalts in early Precambrian assemblages always display more or less alteration. Such a substitution seems justified since the isotopic composition of lead in modern galena (*4*) and that in young potassium feldspars (*5*) lie within the range of values covered by lead in young oceanic basalts.

In studying old rocks, the isotopic composition of lead from both granitic rocks and galena ore bodies should be determined for several reasons. The age of granites and pegmatites can be determined by the conventional methods of geochronology, whereas the age of ore bodies must usually be inferred. On the other hand the concentration of lead in minerals of granitic rocks is in the parts-per-million range, creating two difficulties not present with ore samples. First it is necessary to make corrections for radiogenic lead produced by the uranium and thorium in a mineral, even in potassium feldspars, which have the lowest uranium-lead and thorium-lead

Table 1. Mineral ages from Algoman granites and pegmatites at Manitouwadge, Ontario. MG-17-1 and MG-17-d are light- and dark-colored fractions separated from a single sample of granite. The light fraction contains 257 parts of uranium per million; the dark fraction, 701 ppm of uranium. Observed Sr^{87} was 92 percent radiogenic for MG-20; 47 percent radiogenic for MG-45.

Rock	Mineral	Age (million years) obtained by various methods				
		Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}	Pb^{208}/Th^{232}	Sr^{87}/Rb^{87}
MG-17-l	Zircon	2500	2610	2700	2710	
MG-17-d	Zircon	2420	2560	2670	2300	
MG-17	Biotite					2630
MG-20	Microcline					2590
MG-45	Microcline					2560

ratios of any of the minerals available in granitic rocks. Second, the low lead concentrations increase susceptibility to contamination from external sources. Contamination of lead in potassium feldspars by relatively mild metamorphic episodes (ones that did not seriously alter rubidium-strontium ages of the mineral) has been demonstrated in two localities (*6, 7*). Galena contains negligible amounts of uranium and and thorium, making corrections for internally produced radiogenic lead unnecessary. Since lead is a major constituent of galena, it is difficult to contaminate ore by lead from external sources.

Data in our studies are from granitic rocks and lead ores from the Superior Province of North America, where mineral ages have generally been found to be 2500 to 2700 million years (*8*). Doe, Tilton, and Hopson (*7*) separated lead from five potassium feldspars taken from granites and pegmatites in the vicinity of Rainy Lake in northern Minnesota. The feldspars were taken from Algoman rocks, which are the younger, post kinematic rocks of the area. Rubidium-strontium ages of 2550 million years have been reported for these granites (*9*), while Anderson and Gast (*10*) determined from lead isotopes an age of 2650 million years for zircon from an Algoman granite in northern Minnesota. The Minnesota feldspar samples used for the lead work were separated from the rocks used in the age determinations by Goldich *et al.* (*11*). Biotite from the rocks gives potassium-argon age values of 2400 to 2600 million years, indicating that the area has not experienced severe thermal metamorphism since that time. In interpreting the Minnesota data on lead, it was necessary to make substantial corrections for radiogenic lead produced internally over the past 2600 million years by the uranium in the feldspars. Since galena does not occur in the Rainy Lake area, the isotopic composition of feldspar lead was compared with that of lead from galena at Manitouwadge, Ontario, about 300 km to the northeast (*4*). The Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios of the galena and corrected ratios in feldspar lead agreed rather closely. The Pb^{208}/Pb^{204} ratios of galena and of feldspars agreed within error limits without corrections. These results suggested that the isotopic composition of galena lead was a good approximation of the isotopic composition of lead in the granite when it crystallized. It was also apparent that if the Manitouwadge galena were assigned an age of 2600 million years, and if this value were used to calculate the age of the earth, an age of more than 4550 million years would be obtained.

We now report additional studies at Manitouwadge that enable data from granite and from ore to be compared with greater confidence. We have again determined the isotopic composition of lead and the mineral ages for samples taken from the Algoman granites of the area according to Pye's classification (*12*). The mineral ages are given in Table 1. The ages for zircon, as determined by various methods, are nearly concordant and indicate an age of approximately 2700 million years. If the age discordances are interpreted according to a continuous diffusion mechanism for loss of lead (*13*), an age of 2750 million years results. Since biotite age values are very sensitive to metamorphism (*14*), the age found for this mineral shows that no severe metamorphism has affected the rocks in this area for the past 2600 million years. We are also determining rubidium-strontium age values for the granites using total rock specimens. Of four granites studied thus far, three fit a 2690-million-year isochron within the limits of experimental error, and yield a value of 0.701 for the initial ratio Sr^{87}/Sr^{86} when the Sr^{86}/Sr^{88} ratio is normalized to 0.1194. The fourth sample plots off the isochron in the direction of a younger age. The combined data point to an age of 2600 to 2750 million years for the Algoman granites. The ore bodies were presumably emplaced at about the same time, although after the granites (*12*).

The isotopic composition of lead from four feldspar and two galena samples are given in Table 2. The isotopic compositions are for the samples as prepared, without acid-washing unless indicated. The isotopic ratios are shown graphically in Fig. 1, along with the Rainy Lake samples of Doe, Tilton, and Hopson (*7*). The line through the points representing ratios in feldspar is a "secondary isochron," giving the pattern expected if the isotopic ratios of lead in the feldspars and galenas were identical 2700 million years ago, but have changed due to the decay of the small amounts of uranium present in the feldspars. Within error limits, the feldspars conform to this hypothesis. Even more convinc-

Table 2. Isotopic composition of lead at Manitouwadge, Ontario.

Source of lead	Pb^{206}/Pb^{204}	Pb^{206}/Pb^{207}	Pb^{206}/Pb^{208}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
		Feldspar			
MG-19	13.69	0.9341	0.4076	14.66	33.59
MG-19 (acid-washed)	13.57	.9284	.4057	14.62	33.45
MG-45	13.61	.9245	.4059	14.72	33.53
MG-20	13.92	.9481	.4148	14.68	33.56
MG-20 (acid-washed)	13.71	.9366	.4089	14.64	33.53
MG-41	14.16	.9616	.4211	14.73	33.63
		Galena			
Geco Mine	13.30	.9166	.3960	14.51	33.59
Willroy Mine	13.30	.9149	.3961	14.54	33.58
Average from three mines*	13.40	.9202	.3997	14.57	33.54
		Standard			
Caltech lead standard, average of five determinations	16.63	1.0726	.4574	15.51	36.35

* Data from Ostic (*16*).

Table 3. Age of the earth calculated for various assumed ages of Manitouwadge galena. Constants used in calculations are: for primordial lead, $Pb^{206}/Pb^{204} = 9.54$ and $Pb^{207}/Pb^{204} = 10.27$; for Manitouwadge galena, $Pb^{206}/Pb^{204} = 13.30$ and $Pb^{207}/Pb^{204} = 14.52$; and for decay constants, $U^{238} = 1.54 \times 10^{-10}$ yr^{-1} and $U^{235} = 9.72 \times 10^{-10}$ yr^{-1}.

Age of galena (million years)	Age of earth (million years)
2600	4800
2700	4750
2800	4700

ing evidence linking the feldspar and galena lead is the close agreement of all the Pb^{208}/Pb^{204} ratios in Table 2. From these observations we conclude that the galena data may be taken to characterize the isotopic composition of lead associated with the igneous activity that produced the Algoman granitic rocks at Manitouwadge 2600 to 2700 million years ago. The granitic rocks in the Rainy Lake district were probably formed with lead of very similar isotopic composition.

The age of the earth can be calculated from the Manitouwadge lead data using the same assumptions outlined at the beginning of this report, along with the additional requirement of assigning an age to the rocks. The increments of radiogenic Pb^{207} and Pb^{206} in the granitic or galena lead relative to meteoritic lead give a measure of the time elapsed from the formation of the earth to the formation of the granite. This interval is calculated by the equation given in the introductory paragraph of this report, substituting for the term R the value appropriate for the isotopic composition of uranium at the assumed time of crystallization of the granite. When this value is added to the age of the granite, an age is obtained for the earth. Calculated values for the age of the earth resulting from three different assignments of age for the granites are given in Table 3. All values for the age of the earth given in Table 3 are greater than those obtained from the calculations we have mentioned which have used modern lead. In this report we use an age of 2700 ± 100 million years for the granites, which yields a value of 4750 ± 50 million years for the age of the earth. We emphasize that the uncertainty is a formal one, based on the assumed correctness of the constants and mathematical model. The extent of actual uncertainty is difficult to estimate, but is larger than the formal one.

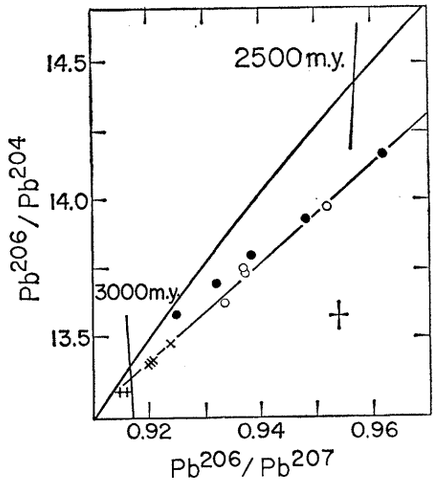

Fig. 1. Pb^{206}/Pb^{204} ratios plotted against Pb^{206}/Pb^{207} ratios for leads from Superior Province, North America. ○, granites and pegmatites from Rainy Lake and northern Minnesota; ●, pegmatites near Manitouwadge, Ontario; ×, Manitouwadge galena described by Ostic (*16*); +, Manitouwadge galena, this report. Cross at lower right represents approximate analytical uncertainty. Lines labeled in millions of years are isochrons based on an age of 4550 million years for the earth and values of 9.54 and 10.27 for the initial Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios, respectively. See text for explanation of line through points.

Since the Manitouwadge–Rainy Lake data represent an extremely small part of the areal extent of the Superior Province, additional data are required to ascertain whether the results are of more than local significance. Isotopic data for lead from galena ores given in the compilation by Russell and Farquhar (*15*) permit a preliminary evaluation of this problem. Their data show that galena deposits along a 1100-km traverse across the Superior Province from Noranda, Quebec, to Kenora, Ontario, generally contain lead quite similar in isotopic composition to that at Manitouwadge. We think, therefore, that the data presented here characterize lead from a substantial portion of the Superior Province.

Ostic, Russell, and Reynolds (*4*) have reported a somewhat different method of calculating the age of the earth that is based on the curvature of the line describing lead evolution as defined by a number of galena samples with ages varying from 0 to approximately 3000 million years. They obtained a value of 4540 million years for the age of the earth, one in good agreement with earlier estimates. Their calculation is strongly influenced by the choice of Manitouwadge lead for the sample in range of 2500 to 3000 million years. Using the compilation by Russell and Farquhar (*15*) we compared data for the isotopic composition of lead from galenas of the Southern Rhodesian Shield of Africa (where mineral ages of 2600 to 2700 million years have also been found) with data for galenas from the Superior Province in the Canadian Shield of North America. Such a comparison shows that the African leads appear to have evolved in sources with higher uranium-lead ratios than did the North American galenas. Use of the African galenas in place of Superior Province galena would increase the age for the earth obtained by the method of Ostic, Russell, and Reynolds. The evidence from young volcanic rocks that many leads have not had a closed system for isotopic evolution and the fact that the African and North American leads are different introduce uncertainty into their results.

There are two simple ways of interpreting the new experiments. The earth may be approximately 200 million years older than previously supposed, having an age of about 4750 million years. If the difference between our results and the earlier ones is due to failure of the closed-system assumption over the past 2700 million years, the failure is in the direction of increase of uranium with respect to lead in the source material for the lead in granites and galenas. If the increase also occurred in the source material prior to 2700 million years ago, calculations show that an age of over 4800 million years is possible. However, the age calculation also contains the assumption that the isotopic composition of lead in the earth was initially the same as that in the troilite phase of iron meteorites. This assumption may be incorrect. We emphasize that the calculation leading to the value of 4750 million years is as good as, if not better than, any of the previous calculations of the age of the earth, particularly those based on modern terrestrial lead, where errors due to failure of the closed-system assumption may be quite large. In any event, interesting effects have been found that indicate the desirability of obtaining new data for the isotopic composition of lead from very old rocks and ores on all continents.

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Geology of the Central Portion of the Queen Maud Range, Transantarctic Mountains

Abstract. *The geologic section consists of a folded and metamorphosed basement complex of geosynclinal and nearshore sediments and intrusives, a thick sequence of nearshore and terrestrial sediments of middle to late Paleozoic age, and thick diabase sheets and basalt flows of Jurassic age. Block faulting, probably during the Miocene age, produced the range, which has been carved into its present form by glaciers.*

The portion of the Queen Maud Range, Transantarctic Mountains, between the meridians 174°W and 176°E and the parallels 84°10′S and 86°S was surveyed by field parties from Texas Technological College during the austral summers of 1962–63 and 1964–65.

Outlet glaciers transect the range in a nearly north-south direction. These and their tributaries form a trellis pattern which may be fault-controlled in part. Near the central north-south line of the area the Shackleton Glacier descends at the rate of about 16.5 m/km through the range from the polar plateau (elevation 2200 m) to the Ross Shelf Ice (elevation about 150 m). The rocks are best exposed for study along the confining walls of this glacier and its tributaries. Fewer outcrops are present along the glaciers to the east and west. The most prominent landmark in the area is Mount Wade (elevation 4750 m), which crests at the northern end of the Wade-Finley ridge at latitude 84°2′S, longitude 174°15′W.

The central portion of the Queen Maud Range has had a geologic history similar to that of the Transantarctic Mountains as a whole (*1*, *2*) (Fig. 1). In late Precambrian-Cambrian time there was deposited in a geosynclinal environment a thick sequence of graywackes which may have been deformed by orogenic processes prior to the deposition of a thick series of quartzites, conglomerates, calcareous arenites, and limestones. An orogeny in late Cambrian or early Ordovician time produced fold mountains, the axes of which trend generally east-west. Calc-alkalic plutons were intruded into the cores of these mountains. Erosion leveled these mountains, and during Devonian to Triassic time a sequence of nearshore and terrestrial sediments was deposited. These sediments are the Beacon rocks, which have widespread distribution in East Antarctica. During the Jurassic period diabase was intruded in great quantities into these sediments and to a lesser extent into the basement complex in sheets, dikes, and irregular masses. Extrusions of similar material in great flows occurred simultaneously along the southern margin of the area. Block faulting during the Mid-Cenozoic age produced the Queen Maud Range, which in this central section appears to be a major tilted block dipping gently to the south. Late Cenozoic and recent glaciations have produced the present geomorphic features.

Two distinct sequences of metasediments are present in the basement complex. In the Ramsey Glacier area there is a minimum of 3500 m of metagraywackes and slates. This unit is very similar lithologically to the type Goldie formation, Beardmore Group (*3*), and is tentatively correlated with it. The second sequence crops out along both sides of the Shackleton Glacier. It is a thick unit comprised of quartzites, conglomerates, calcareous quartzites, and marbles. The type locality is Taylor Nunatak, latitude 84°55′S, longitude 176°W; the formation is here named the Taylor. No contacts between the two sequences of metasediments were observed and their age relationships are not known.

The intrusives associated with the metasediments are mostly calc-alkaline. Granodiorites and adamellites are common and are the principal constituents of a major pluton centered in the northern portion of the Shackleton Glacier. Smaller bodies of granite are distributed about the periphery of the pluton. These intrusives are tentatively correlated with the Granite Harbour Intrusives of Victoria Land (*4*), which have been dated radiometrically as Upper Cambrian to Ordovician (*6*).

The Beacon sequence is divided into five units. The oldest rests on the erosion surface on the basement complex. It is 61.5 m thick and is comprised of a basal portion of 47.5 m of gray to yellow conglomerate and quartzite sandstone topped by thin layers of siltstone. Above the basal portion is a cliff-forming, light yellow, fine-grained, massive, partly conglomeratic quartzite, which is 14 m thick. In age it may be the equivalent of the Alexandra formation, Lower Carboniferous, or the Pagoda Tillite, Upper Carboniferous (*4*). Tentatively we have named it the Butters formation. The type locality is Mount Butters, 84°53′S, 177°30′W.

The second unit is the Mackeller (*4*). The basal section consists of 136.5 m of dark gray to black, hard, silty shale which weathers to a reddish color. Thin, gray to white beds of siltstone are interbedded with shale. The upper portion of this unit consists of 167 m of buff-colored, fine- to coarse-grained sandstone interbed-