[AMERICAN JOURNAL OF SCIENCE, VOL. 254, SEPTEMBER 1956, P. 555-566]

# Rb/Sr AGE, ELEMENTAL AND ISOTOPIC ABUNDANCE STUDIES OF STONY METEORITES

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ABSTRACT. The concentrations of Rb and Sr in two chondritic meteorites have been determined by the stable isotope dilution method, and Sr isotope abundances of the chondrites and an achondrite with a large $\frac{Sr}{Rb}$ ratio investigated. Age and original $^{87}Sr$ relative abundance relationships for the chondrites and the Earth are given.

Homestead chondrite Sr shows a 5% enrichment in the radiogenic isotope $^{87}Sr$, compared to a terrestrial standard with isotope abundances nearly identical to those of recent oceanic Sr, while the abundance ratios of the other isotopes, 84, 86 and 88, in meteorite and standard are very closely identical. The precision of these measurements (as relative standard deviation) is ± 0.4%. Forest City chondrite Sr appears to be essentially identical in isotope composition. Pasamonte achondrite Sr is identical in 84, 86, and 88 ratios, but depleted by 1.5-3.0% in $^{87}Sr$.

The Rb and Sr concentrations measured for the meteorites, with the metallic phase extracted prior to analysis, are as follows: Homestead, Rb = 4.0 ± 0.4 ppm by weight; Sr = 11.9 ± 0.5, 10.7% metal extracted. Forest City, Rb = 4.3 ± 0.3; Sr = 12.1 ± 0.5, 19% metal extracted. (Total meteorite abundances are given in the text.) The Rb values are lower than those previously accepted.

Recent determinations and estimates of chondrite ages by the U/Pb, K/A and other methods yield values of (4.2-5.2) x $10^9$ years. The abundance of $^{87}Sr$ in Homestead Sr 4.7 x $10^9$ years ago was 0.0682 ± 0.0005, if the half life of $^{87}Rb$ is 61.3 x $10^9$ years, or 0.0671 ± 0.0005 if this half life is 50 x $10^9$ years. Further, our previous determinations of Sr isotope abundances in ancient terrestrial minerals with very high Sr/Rb ratios indicate an $^{87}Sr$ abundance of roughly 0.0675 ± 0.0010 for bulk terrestrial Sr 4.7 x $10^9$ years ago, and the $^{87}Rb$ half life uncertainty does not enter into this extrapolation.

Hence, meteorites and Earth appear to have had identical Sr isotope compositions, including an "original" $^{87}Sr$ concentration ($^{87}Sr_O$) of 0.0683 ± 0.0010 approximately 4.7 x $10^9$ years ago. This evidence admits the possibility of a contemporaneous origin of these chondrites and Earth about 4.7 billion years ago.

## INTRODUCTION

In a previous paper (Herzog and others, 1954) we reported preliminary analytical work on the Homestead meteorite. A significant enrichment of $^{87}Sr$ had been found, and from optical spectrographic analyses the Sr/Rb ratio was believed to be known to a precision of ± 30%. However, the accuracy of the optical spectrographic data, especially the Rb content of the meteorite, was in doubt.

Isotope dilution analyses for Rb and Sr have now been made in duplicate for the Homestead sample. In addition, the isotopic composition of this meteorite's Sr has been more accurately determined by another analysis, using refined techniques (Herzog and Pinson, 1955b).

To calculate the age of a meteorite, it is necessary to know its $^{87}Sr$ abundance when it formed. We hoped to obtain this information indirectly by measuring the Sr isotope abundances in a meteorite with a Sr/Rb ratio sufficiently high (>100) that $^{87}Rb$ decay-produced $^{87}Sr$ would produce only a negligible increase in total meteorite $^{87}Sr$ abundance in several billion ($10^9$) years. Published analyses of the achondritic Pasamonte meteorite (Urey and Craig, 1953) indicated that it had a Ca/K ratio of 170, and hence that its Sr/Rb ratio should be greater than 100. We obtained a very small sample of Pasamonte from the National Museum in Washington in 1954 through the kindness of Mr. E. P. Henderson. The Sr from 0.3 gm of this material was separated, and its isotopic composition was analyzed. The analysis for $^{87}Sr$ was unsuccessful because the small $^{87}Sr$ signal obtained was swamped by a small amount of contamination $^{87}Rb$ (the ionization efficiency of the surface ionization source used in this work is more than 1000 times greater for Rb than for Sr), although analysis for the other isotopes was successful. The remaining gram of this material was set aside pending improvements in technique which would warrant its use. Since in the interim a technique for more complete separation of traces of Rb from Sr samples, and an increase of at least a factor of 50 in instrumental Sr sensitivity have been achieved (Herzog, Pinson, and others, 1955, p. 18, 22), analysis of a new Pasamonte Sr sample has been started. This analysis indicates that Pasamonte Sr is indeed lower in $^{87}Sr$ content than standard Sr by at least 1.5 percent.

When the first Pasamonte analysis failed, it was decided to analyze the Forest City chondrite. A sample was available, and previous spectrographic analyses (Pinson, 1951) indicated that it had a Sr/Rb ratio double that of Homestead, which, if true, would permit moderately precise solution for original meteoritic $^{87}Sr$ and age by extrapolating the $^{87}Sr$ abundances in the two meteorites backwards in time until they were equal. However, isotope dilution analysis showed that the Sr and Rb contents of the meteorites were very similar, and hence that the reported differences were due to experimental error, and this pair of meteorites was unsuited for the determination of $^{87}Sr_O$. Indeed, the isotope dilution run data indicate that $^{87}Sr/Sr$ in Forest City is identical to Homestead $^{87}Sr/Sr$. (A separate isotopic analysis run on unspiked Forest City Sr has not yet been made.) Thus, at present, the predicted original $^{87}Sr$ abundance has not been observed; however, sufficient information has been gathered to allow a well founded prediction of this value for both terrestrial and meteoritic matter: very probably, $^{87}Sr_O = 0.0683 \pm 0.0010$, and this range includes a 20% uncertainty in the $^{87}Rb$ half life. Also, the Rb and Sr and isotope analyses made are of some general interest; we have decided therefore to present the information we have at present, even though the age portion of the work is incomplete.

## ANALYTICAL PROCEDURES

Descriptions of the meteorites analyzed are contained in Prior's (1953, p. 124, 157) recent catalogue. For these analyses, the metal phase was extracted magnetically. Optical spectrographic analysis had shown the metal and sulfide phases of meteorites to contain negligible Sr and Rb compared to the silicate phase. From the Homestead chondrite, 10.7% metal was extracted, and from Forest City, 19%. The sulfide phase in chondrites averages about 5% by weight; this proportion is fairly constant. Sulfide was not removed because of the difficulty of the separation.

All concentrates for mass spectrometric analysis were prepared by dissolving samples in HF, with the exception of the first Homestead Sr isotope analysis run. With this exception, in all cases small amounts of insoluble residue, less than 1% of sample weight, were left. Optical spectrographic analysis showed these residues to contain negligible Rb and Sr. In the first analysis, the sample was fused with $Na_2CO_3$. A tracer experiment showed that a considerable (> 5 $\mu$gm) amount of Sr contamination had been introduced, necessitating a large correction to the observed $^{87}Sr$ abundance; therefore, in the new analysis, $Na_2CO_3$ fusion was not used. Negligible contamination Sr was introduced, a much larger Sr sample was successfully applied to the filament, there was no Rb interference present, measurements were made on a less sensitive instrument scale, and a much superior analysis was obtained.

*Contamination.*—Stable isotope tracer experiments indicate that less than 0.5 $\mu$gm of Sr contamination are introduced in the processing of one-gram samples by present procedures. and in fact no Sr contamination has been detected. Rb contamination level for our processing of meteorite samples has not been measured directly as yet. However, a contamination level of less than 0.1 $\mu$gm/gm of sample is indicated (as described below) by a similar experiment performed for K contamination (Greenwalt, Herzog, and Pinson, 1955) for a procedure very similar to that used for our Rb analyses. But since the Rb analyses required one additional step (ion exchange column separation), it is possible that the Rb contamination level may have been slightly higher in these experiments.

A 6″ radius, 60° sector-field machine with a thermionic source was used for the mass spectrometric work reported. Rb and Sr ions were produced from RbCl, $Rb_2HPO_4$, and SrO on clean or oxidized Ta ribbon supports. Procedures used have been described in detail in previous annual reports of the Nuclear Geophysics Section (Herzog and others, 1954, 1955) of this department.

## Sr AND Rb ABUNDANCES

Table 1 gives the Rb and Sr contents of the combined silicate and sulfide phases of the two chondrites analyzed. Table 2 includes the comparable values for total meteorite.

TABLE 1

Sr and Rb Contents of Combined Silicate and Sulfide Phases of Two Meteorites, by Isotope Dilution

| Sample | % Metal extracted* | Dates of analyses | Sr ppm | Rb ppm | Sr/Rb |
|---|---|---|---|---|---|
| Homestead I | 10.7 | 15 Oct.-2 Nov. 1954 | 12.3 | 4.4 | 2.8 |
| Homestead II | 10.7 | 20-30 Nov. 1954 | 11.5 | 3.6† | 3.2 |
| Homestead Avg. | 10.7 | — | 11.9 | 4.0 | 3.0 |
| Forest City | 19.0 | 1-15 Apr. 1955 | 12.1 | 4.3** | 2.8 |

* See "analytical procedures" above for discussion of Rb, Sr content distribution among the three meteorite phases.

** Edwards and Urey (1955) have recently measured Rb in Forest City; see table 2 for comparison of values.

† It is not known whether the 20% difference between the first and second Homestead Rb analyses is due to contamination in the first run, or merely indicative of total analysis reproducibility for low level Rb analyses at this time. Much-improved chemical techniques were used for the second analysis, but the mass spectrometer run was subaverage. A third Rb analysis is in progress.

TABLE 2

Comparison of Total Chondrite Strontium and Rubidium Analyses

All analyses expressed as parts per million by weight

| | Rubidium | | | | Strontium | | |
|---|---|---|---|---|---|---|---|
| Meteorite | APK | Rev | EU | HP | P | PAF | HP |
| Homestead | 12.0 | 6 | — | 3.6 | 12 | 18 | 10.6 |
| Forest City | 6. | 3 | 5.8 | 3.5 | 10 | 15 | 9.8 |
| Waconda | 10. | 5 | 4.0 | — | 9 | 11 | — |
| Barratta | 13. | 6 | 6.0 | — | 7 | 9 | — |
| Avg. chondrite | 8.3 | 4.0 | 5.2 | — | — | 11 | — |

APK = Ahrens, Pinson, and Kearns, 1952.
Rev = APK revised, on basis of isotope dilution Rb standardization.
EU = Edwards and Urey, 1955, employing distillation of Rb and flame photometer analysis, ± 25% stated precision.
HP = Herzog and Pinson, present work.
P = Pinson, 1951, thesis; Sr in W-1 diabase = 190 $\mu$gm/gm used as standard of comparison.
PAF = Pinson, Ahrens, and Franck, 1953, a revision of P, using 290 $\mu$gm/gm for W-1 Sr, and additional analyses.

Avg. Chondrite = Average of 21 analyses for APK and PAF, 3 analyses for EU.

The Rb abundances reported in table 1 are lower than previous analysts have reported for other fragments of the same meteorites, as shown in table 2. Recent isotope dilution experiments (Herzog and Pinson, 1955a, and in press) indicate that all previous M.I.T. Cabot Spectrographic Laboratory Rb analyses, including those of 21 chondrites (Ahrens, Pinson, and Kearns, 1952), are very probably about 2.1 times too high and should be revised. This estimate is based on 8 samples analyzed by both methods. Such revision gives 4.0 ± 0.6 ppm for the Rb content of average chondrite.

The Sr abundances reported are very similar to those found by Pinson (1951), who used 190 ppm for the Sr abundance in the standard diabase, W-1, which was his measurement standard. The values published by Pinson, Ahrens, and Franck are higher because the average of several analyses for Sr in W-1 at various laboratories, 290 ppm, was used to recalculate the measurements. We have recently found 177 ± 7 ppm Sr in W-1 by isotope dilution (Herzog and Pinson, 1955c).

The data presented by Ahrens, Pinson, and Kearns yielded a ratio for K/Rb = 100 (840 ppm K, 8.3 ppm Rb for average chondrite). Diminishing the Rb value found by a factor of 2.1 to make these analyses consistent with the isotope dilution determinations of Rb in identical samples, as discussed above, yields K/Rb = 210. Our isotope dilution determinations of K/Rb for Forest City and Homestead average 265 (this work, and Greenewalt, Herzog, and Pinson, 1955), while the average for the three samples analyzed by Edwards and Urey by optical spectrograph is 180. Thus the true K/Rb ratio

[1] Greenewalt and others (1955) found 19 $\mu$gm/gm of contamination K in his recent meteorite processing, indicating about 19/220 $\cong$ 0.1 $\mu$gm/gm of Rb contamination for this procedure, since the K/Rb ratios for laboratory contamination and meteoritic matter are very similar. (See, for example, Pinson, Ahrens, and Franck, 1953, for a discussion of the variation of K/Rb in terrestrial materials.) This determination is further discussed in the section on analytical procedures.

for average chondrite now appears to be about 220, with an estimated uncertainty of ± 25%.[1]

## ISOTOPIC ANALYSES OF METEORITE Sr

The isotopic composition of Homestead meteorite Sr is compared to that of a "normal" terrestrial Sr standard as reported by Nier (1938) and also by Herzog and others (1953), in table 3.

As was noted in the introduction, the isotopic analysis made on December 14, 1954 is believed to be greatly superior in quality to the first analysis, made in February, 1954, because of interim improvements in technique. For this reason, the later analysis alone has been used in the age calculations carried out below.

There is only about a 1% difference between the 86/88 ratio measurements of Homestead and terrestrial standard Sr, and in fact the entire difference may represent experimental error, although in general our reproducibility for Sr samples is rather better than this. The 84/88 ratios are similarly in agreement. However, the 87/88 ratios, ratios of a radiogenic to a non-radiogenic isotope, are different by about 5%. The enrichment in radiogenic strontium in the meteorite is real and far outside the limits of analytical error. Considering the measured Sr/Rb ratio, an extreme antiquity is indicated for the meteorite.

An independent isotopic composition analysis of Forest City Sr has not been made as yet. However, its $^{87}Sr$ content can be closely estimated from the isotope dilution data. If we assume that the 84/88 and 86/88 ratios in Forest City Sr are essentially normal (as they are in Homestead and Pasamonte Sr), the calculated $^{87}Sr$ content of Forest City Sr is (7.365 ± 0.050)%, which is identical, within the stated limits of error, with $^{87}Sr$ in the Homestead meteorite, (7.335 ± 0.030)%.

Pasamonte achondrite Sr is also identical, within the stated limits of error, with our standard Sr in its relative 84, 86, and 88 contents but is depleted in 87 by at least 1%. We have not yet had a completely satisfactory analytical run on this sample, in part because we had available only 0.2-0.5 gram per run.

In the first run, the Rb current was so large that $^{87}Sr$ could not be calculated with useful precision; also, the Sr current was only slightly above the detectability threshold. In the second run, the Rb current was very small, and the Sr current about the same as in the first run, but, in the meantime, instrumental sensitivity had been increased more than 100 fold. However, during part of the run tube pressure was above $1.0 \times 10^{-6}$ mm Hg so that there was some ion beam broadening. As we were most interested in establishing an *upper limit* for Pasamonte $^{87}Sr$, we corrected conservatively for these effects in obtaining the values (e.g., 87/86 max = 0.0703 ± 0.0003) listed in table 3. $^{85}Rb/^{87}Rb$ was assumed to be 2.60, which is the ratio in ordinary rubidium, although "memory" effects from previous isotope dilution runs often cause lower ratios in the accumulated Rb inside the analytical mass spectrometer; also, no pressure correction was made. If, instead, reasonable pressure broadening corrections are made, and the $^{85}Rb/^{87}Rb$ ratios observed

TABLE 3

Meteorite Isotope Abundances

Mass spectrometric measurement precision, as relative standard deviation, for all measurements is ± 0.4%, except: ± 2.0% for the 1954 Pasamonte ratios reported and all 84 measurements, and ± 0.6% for $^{87}$Sr in Forest City.

| Run | No. sets | Observed Ratios 87/88 | 86/88 | 84/88 | 87/86 | Relative Abundances 84 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|
| Homestead | | | | | | | | | |
| 9 Feb. 1954 (Contaminated) | 148 | .0875 | .1190 | .0069 | .735 | .0057 | .0981 | .0722 | .8240 |
| 14 Dec. 1954 (Scales changed)* | 50 | .0892 | .1186 | .0069 | .752 | .0057 | .0976 | .0734 | .8233 |
| 14 Dec. 1954 (Scales not changed)* | 92 | .0890 | .1181 | .0069 | .754 | .0057 | .0973 | .0733 | .8237 |
| Average for 14 Dec. analysis | 142 | .0891 | .1183 | .0069 | .753 | .0057 | .0974 | .0733 | .8235 |
| Forest City | | | | | | | | | |
| 1-15 Apr. 1955 (isotope dilution)** | 20 | — | (.1194) | (.0068) | — | — | — | .0736** | — |
| Pasamonte | | | | | | | | | |
| 27-29 Oct. 1954 | 48 | — | .1210 | .0067 | — | — | — | — | — |
| 10-20 Aug. 1955 | 111 | .0842† | .1197 | .00682 | .703† | .00563 | .0989 | .0695† | .8259 |
| Nier's Normal Sr | | .0850 | .1194 | .0068 | .712 | .0056 | .0986 | .0702 | .8256 |

* For some groups of peak sets, all isotopes were recorded at the same sensitivity scale setting of the strip chart recording potentiometer, while for other groups sensitivity was changed in such a way as to make the recorded peak heights of the less abundant isotopes comparable to the trace of the abundant 88 peak.

**Determined incidental to isotope dilution analysis for Sr concentration. $^{87}$Sr solved for on assumption 84/88 and 86/88 are identical to values for standard Sr ("Nier's Normal Sr").

† Maximum, as small Rb contamination and pressure broadening corrections were made conservatively. Values up to 1.5% smaller are permitted by the uncertainties in these corrections (e.g., $0.703 \geqslant {}^{87}Sr/{}^{86}Sr \geqslant 0.691$).

during the run are used in correcting for $^{87}Rb$, $^{87}Sr$ values up to 1.5% lower (e.g., 87/86 = 0.0691 ± 0.0003) result. We believe the true $^{87}Sr$ value for Pasamonte lies within this range, possibly nearer the upper limit. We plan another analysis to determine this important value more exactly.

## PREMISES OF Rb/Sr AGE DETERMINATION

For the calculation of the Rb/Sr age of a meteorite the following quantities must be known:

(1) The Sr and Rb content of the sample.

(2) The fraction of Sr which is radiogenic, hence,

  (a) The present fraction of $^{87}Sr$ in total sample Sr.

  (b) The original fraction of $^{87}Sr$ in total sample Sr.

(3) The present fraction of $^{87}Rb$ in total sample Rb, and the variation of this fraction in past time.

(4) The decay constant of $^{87}Rb$, implicit in (3).

Also, a necessary condition for age determination is that the sample shall have been a closed system in so far as ingress and egress of Rb and Sr is concerned, since the object was formed.

Items (3) and (4) have been previously discussed (Herzog and others, 1954) and will not be repeated here.

The condition that the sample shall have been a closed system is a serious one to be met in *all* radioactivity methods of age determination. This condition is perhaps more favorably satisfied by meteorites than any other rock or mineral samples analyzed. If meteorites have been isolated in space, they have not been subjected to metamorphic processes and to possible leaching by ground or magmatic waters as are terrestrial samples. However, it should be noted that laboratory experience indicates that the alkali metals K, Rb, and Cs are copiously vaporized, in vacuo, at temperatures below red heat. There is some evidence that most meteorites have not undergone such heating since their last crystallization. An example of this evidence is the existence of Widmanstätten figures in metal meteorites. However, perhaps the strongest evidence is the near constancy of the alkali trace element content of chondrites, which has been investigated by optical spectrograph (Ahrens, Pinson, and Kearns, 1952; Pinson, Ahrens, and Franck, 1953; Edwards and Urey, 1955). Had some chondrites undergone heating (as for example by passing close to the Sun), these meteorites would be depleted in volatile elements such as K and Rb. Numerous analyses have failed to find any anomalously alkali-low chondrites. The Homestead and the Forest City chondrites are normal in their alkali contents, and it is tentatively concluded that these two chondrites have not been heated since their formation.

The present fraction of $^{87}Sr$ in total sample Sr, item (2a), has been determined. However the original fraction of $^{87}Sr$, item (2b), cannot be directly determined, but must be estimated by methods such as those discussed below. It should be emphasized that this difficulty is inherent in most radioactivity age determination methods. For example, most ages by the U/Pb, Pb/Pb, or Th/Pb methods assume a knowledge of the initial isotopic composition of Pb. The case of uraninite U/Pb ages, where only negligible amounts of common Pb are present in the sample, is directly comparable to the case of lepidolite, where often only negligible amounts of common Sr are included in the mineral. In both cases knowledge of daughter element isotope composition at the time of crystallization of the mineral is superfluous.

## AGE CALCULATIONS

For the Homestead meteorite all the quantities necessary for age determination are known except the initial isotopic composition of the Sr, and this knowledge may not be obtained directly. However, the near identity of the non-radiogenic isotope ratios 86/88 and 84/88 in meteorites and terrestrial Sr may be used as an argument that initially terrestrial and meteorite Sr had the same isotopic composition.

Table 4 gives two "ages" calculated on two assumptions as to the initial Sr isotopic composition of Homestead meteorite. [0.2785 (Nier, 1950) was used for the relative atomic abundance of $^{87}Rb$.] Next, an age of 4.7 x $10^9$ years is postulated for meteorites, and the abundance of $^{87}Sr$ at that time in Homestead meteorite Sr is computed on the basis of two possible $^{87}Rb$ half lives.

*Discussion.*—1. A "minimum age" of 2.8 x $10^9$ years is obtained if the initial abundance for $^{87}Sr$ is assumed to have been 0.0702. This is the relative abundance in the terrestrial reagent Sr standard previously mentioned (Nier, 1938; Herzog and others, 1953). We have been unable to discover the geological source of this "standard Sr"; however, the value 0.0702 is typical for Sr extracted from limestones of Paleozoic age (Herzog and others, 1954).[2] The $^{87}Sr$ abundance for a Recent or Pleistocene coquina from the Florida east coast (Herzog and others, 1954) is 0.0705 ± 0.0003.

2. Our analysis (above) indicates that $^{87}Sr/Sr$ in Pasamonte achondrite Sr today is less than 0.0695 ± 0.0003, and its Ca/K ratio is so high that, very probably, $^{87}Sr/Sr$ in the meteorite has changed very slightly, perhaps 0.0002 ± 0.0002, in 5 × $10^9$ years. If original $^{87}Sr$ abundances were identical in achondrite and chondrites (as their 84, 86, and 88 abundances are, apparently, identical), a value in the range 0.0687 ± 0.0008 should be used for $Sr_0$ in calculating the chondrite ages.

We have also found terrestrial $^{87}Sr$ abundances as low as 0.0692 ± 0.0005 for ancient calcic plagioclases with Sr/Rb ratios greater than 100. It

TABLE 4

Age and Initial $^{87}Sr$ Abundance Relations for the Homestead Meteorite

| | Initial $^{87}Sr$ content | Half life of $^{87}Rb$ assumed | "Age" in $10^9$ year units |
|---|---|---|---|
| | Assumed | | Calculated |
| 1. | 0.0702 | 61.3 x $10^9$ yrs. | 2.8 ± 0.3 |
| 2. | 0.0692 | " " | 3.7 ± 0.4 |
| | Calculated | | Assumed |
| 3. | 0.0682 ± 0.0005 | " " | 4.70... |
| 4. | 0.0671 ± 0.0005 | 50.0 x $10^9$ yrs. | 4.70... |

[2] But at least some of the samples analyzed may be "recent" exchanged Sr.

seems reasonable to assume that the meteorite had an initial 87 abundance at least as low. Initial 87 abundances of less than 0.0692 lead to ages greater than 3.7 billion years. A half life of $61.3 \times 10^9$ years was used in both the preceding calculations.

3. Patterson (1955) has found the ages of several meteorites, including Forest City, to be very close to $4.5 \times 10^9$ years. His results appear to us to be the most dependable age measurements made up to the present, especially since the leaching and addition problem that makes terrestrial U/Pb measurements questionable is not present for meteorites. Extreme chondrite antiquity is also indicated by recent K/A age measurements by Wasserburg and others.[3] These recent radioactivity determinations of solar system ages, and estimates based on astronomical data, for the most part fall in the range $(4.7 \pm 0.5) \times 10^9$ years.

If the Homestead age is $4.7 \times 10^9$ years and the $^{87}Rb$ half life is $61.3 \times 10^9$ years, the original relative 87 abundance of Homestead Sr can be calculated as $0.0682 \pm 0.0005$. The value derived, of course, depends on the half life. We have used $61.3 \times 10^9$ years heretofore in order to make possible direct comparison of our results with those of the group at the Carnegie Institution of Washington. This value was selected in 1953 as it was strongly indicated as correct by the then most recent investigations of the half life by counting techniques.

4. However, comparison of our recent age measurements and those of Aldrich and his colleagues at the Carnegie Institution (Aldrich, Tilton, and Wetherill, in press) with the most reliable U/Pb ages for the areas investigated shows a rather consistent difference which would vanish if the $^{87}Rb$ half life was about $50 \times 10^9$ years. A very recent counting determination of the half life, by Geese-Bähnisch and Huster (1954), in which quite elaborate controls and interchecks were used, indicates that the half life may be as low as $43 \times 10^9$ years. Actually, as it is necessary to extrapolate the low energy portion of the beta decay spectrum owing to failure of present techniques below 10-20 KeV, all the counting results are subject at present to an uncertainty of at least 10%, regardless of other factors.

Thus, a calculation based on a half life of $50. \times 10^9$ years is of some interest, and has been included in the table. The corresponding value for $^{87}Sr_O$ is $0.0671 \pm 0.0005$.

## TERRESTRIAL $^{87}$Sr VARIATION

Original $^{87}Sr$ values in the range 0.0665-0.0685 are supported by another line of evidence. Wickman (1948) and others predicted a large variation in the $^{87}Sr$ content of terrestrial Sr during geologic time on the basis of a then indicated crustal Sr/Rb ratio of about 1, or less, and pointed out that such

[3] Recent analyses by Wasserburg and Hayden (1955), using the K/A decay, support this work, and the K/A results of Thomson and Mayne (1955) and Gerling and Rik (1955) also indicate the great antiquity of at least most chondrites. However, these "argon ages" are at present subject to an uncertainty of at least ± 20% in the K/A half life (and the A/Ca branching ratio) of the K decay. Hence, the U/Pb ages, in which two decays, of $^{235}U$ and $^{238}U$, give the possibility of confirmation of results, appear much more trustworthy at this time.

a variation could be used as a dating method for limestones, calcic plagioclases, and other high Sr/Rb ratio minerals. Although many samples of different ages have been analyzed to test this possibility (Herzog and others, 1953, 1954), the expected depletions in $^{87}$Sr have not been found. The lowest abundance observed for a calcic plagioclase of presumed age greater than 1.5 x $10^9$ years, as mentioned above, was 0.0692 $\pm$ 0.0005. On the basis of these studies we now believe that in 4.7 x $10^9$ years the relative abundance of $^{87}$Sr in total terrestrial Sr has varied only between the limits of 0.0675 $\pm$ 0.0010 and the present 0.0705 $\pm$ 0.0003. Our recent finding that one laboratory's Rb determinations used in calculations such as those of Wickman were uniformly too high by a factor of about 2.1 (Herzog and Pinson, 1955) offers at least a partial explanation for the discordance of the predicted and observed variations.

## SUMMARY AND CONCLUSIONS

These investigations indicate that at some time in the immediate vicinity of 4.7 x $10^9$ years ago, silicate meteorite Sr and terrestrial Sr had identical relative abundances of the radiogenic isotope $^{87}$Sr of 0.0683 $\pm$ 0.0010; further, the ratios of the other, not appreciably radiogenic isotopes, 84, 86, and 88, were and are now identical, within the limits of experimental error, $\pm$ 0.5% standard deviation. This evidence admits the possibility that Earth and meteorites may have formed contemporaneously about 4.7 x $10^9$ years ago, and conforms with the U/Pb and K/A evidence recently obtained by others.

These statements rest on the following data:

1. The silicate-sulfide phases of the Homestead and Forest City chondrites are closely similar—identical, within the limits of error of the present measurements—in Sr and Rb concentration (12.0 $\pm$ 0.5 and 4.0 $\pm$ 0.4 p.p.m. by weight) and ratio, and in Sr isotope composition, both having $^{87}$Sr/Sr today = (7.35 $\pm$ 0.05)%. If the $^{87}$Rb half life is (55 $\pm$ 6) x $10^9$ years, $^{87}$Sr/Sr concentrations 4.7 x $10^9$ years ago in these meteorites were 0.0677 $\pm$ 0.0010.

2. $^{87}$Sr/Sr in Pasamonte achondrite material today = (6.89 $\pm$ 0.08)%. Since the Ca/K ratio in this meteorite is, reportedly, 170, this value has in all probability not increased more than (0.02 $\pm$ 0.02)% in 4.7 x $10^9$ years and was then (6.87 $\pm$ 0.08)%; this value is insensitive to even large errors in the assumed $^{87}$Rb half life.

3. Studies of ancient terrestrial minerals with very large Sr/Rb ratios ($>$100) indicate that terrestrial $^{87}$Sr/Sr was in the range (6.75 $\pm$ 0.10)%, 4.7 x $10^9$ years ago. This result is independent of the $^{87}$Rb half life as the sample ages were estimated by other methods.

Unfortunately, the original $^{87}$Sr data so far obtained are not sufficiently precise to make possible a decision as to the true $^{87}$Rb half life.

The average Sr content of chondrites, our analysis indicates, is probably 10 $\pm$ 2 ppm by weight, in agreement with the most recent optical spectrographic analyses (Pinson, 1951; Pinson, Ahrens, and Franck, 1953). However. chondrites probably average only 4.0 ± 0.6 ppm Rb instead of the 8.3 ppm previously indicated (Ahrens, Pinson, and Kearns, 1952). Generalization from two chondrite analyses is justified because of the demonstrated uniformity of composition of the silicate-sulfide phases of chondrites (Pinson, 1951. et. seq.).

The corrected Rb abundances and verified K analyses for these meteorites indicate, in addition, a K/Rb ratio of 220 ± 50 for average chondrite matter.

ACKNOWLEDGMENTS

This work was supported by the U. S. Atomic Energy Commission under contract AT (30-1)-1381. The authors wish to express their appreciation for this support. The cooperation of Mr. E. P. Henderson of the U. S. National Museum and Professor Clifford Frondel of the Geological Museum of Harvard University in furnishing meteorite samples used in this investigation is gratefully acknowledged. We also wish to express our appreciation to Dr. L. H. Ahrens who first stimulated our interest in trace element studies in meteorites.

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