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Rb - Sr AGES OF CHONDRULES AND CARBONACEOUS CHONDRITES

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ABSTRACT: Determinations of Rb, Sr and K and Sr isotopic compositions are reported for the carbonaceous chondrites Orgueil, Murray, Mokoia and Lance, the hypersthene chondrite Peace River, and four chondrules from the Peace River meteorite. Rb and K show a decrease in abundance from Type I to Type III, in accordance with previous work; Sr is relatively constant. An isochron constructed from the carbonaceous chondrite data alone has an age of 4.46 ± 0.35 AE taking λ Rb^{87} equal to 1.39 x 10^{-11}/year, and an initial Sr^{87}/Sr^{86} of 0.7007. The age becomes 4.74 ± 0.15 AE if the initial Sr^{87}/Sr^{86} is assumed to be 0.6985 (the mean initial value for achondrites), but the residual variance in the regression now becomes greater than experimental error. Most of the residual variance is contributed by the Type III carbonaceous chondrites: one of several possible explanations is that Type III formed some 0.3 AE later than Type I by Rb depletion.

Inclusion of the data for the Peace River chondrite changes the age only slightly to 4.76 AE. The data from the four chondrules scatters widely about this isochron, showing "geological" error and possibly increased experimental error also.

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INTRODUCTION

An accurate determination of the "solidification ages" (Anders, 1962) of meteorites provides one of the important clues to the genesis and subsequent history of meteorites. Although the solidification ages have been determined for a number of chondrites by the Pb-Pb method and the Rb-Sr method by several previous workers, carbonaceous chondrites have not been well represented in these earlier studies. Recent detailed studies on the mineralogy and chemistry of the carbonaceous chondrites have led to some speculations as to the origin and age of these meteorites and provided the impetus for the present work. Similarly, recent studies on individual chondrules from stone meteorites have created the need for age determination of these objects. There are no known solidification ages of individual chondrules and a preliminary attempt was made here, as part of a larger program of isotopic investigations on chondrules.

The Rb-Sr method of age determination is perhaps the only way at present by which solidification ages of small samples such as individual chondrules and rare meteorites can be determined. Besides requiring large samples, the Pb-Pb method is somewhat insensitive in the case of the carbonaceous chondrites because of the very small U/Pb ratios and the consequent non-radiogenic nature of the leads in them (Marshall, 1962). Ages of some of the carbonaceous chondrites have been measured by the K-Ar method, but are subject to the loss of Ar during their lifetimes.

One of the purposes of the present study was to determine the age of the carbonaceous chondrites as a group, without any assumption as to their initial Sr^{87}/Sr^{86} ratio. A similar attempt was made for the chondrules separated from the Peace River chondrite. In both cases, the objective was to compare the ages thus obtained with the solidification ages deduced elsewhere for chondrites and achondrites in order to infer genetic relationships between these objects, -- chondrules, carbonaceous chondrites, and ordinary chondrites.

It must be pointed out here that this paper reports the results of independent investigations done in two separate laboratories. We have purposely chosen to combine all the data here in order to provide a greater cogency and completeness to the topic than would have been possible otherwise.

EXPERIMENTAL PROCEDURES

The determination of the Rb-Sr age of a small meteorite sample involves the following steps, both performed under minimal contamination conditions - 1) An accurate determination of Rb and Sr contents of the sample, and 2) The precise measurement of the isotopic composition of Sr. The details of procedures used were more or less conventional and are as follows:

For the total meteorite samples, a chip or fragment weighing about 0.5 - 2.0 grams was selected from an interior location of the meteorite sample. In the case of chondrules, individual chondrules from the Peace River meteorite were taken each weighing generally about 0.1 - 0.45 grams. In no case were these samples washed externally with distilled water or dilute acids for fear of leaching out loosely bound Rb and/or Sr. Since the sample handling history of any particular sample chosen for our study was known to us in all cases, and stringent precautions were taken in the handling procedures of these meteorite chips or chondrules, it was felt that surficial washing is not only unnecessary but may be dangerous.

In this study, the elemental abundance determination of K, Rb, and Sr, as well as the isotopic composition of Sr were done on a single sample by taking aliquots of the dissolved sample. Chemical separations necessary for extracting the K, Rb and Sr fractions were done by the cation exchange method using Dowex 50W - X8, 200 - 400 mesh, prepurified and washed resin and 25-30 cm long, 0.9 cm dia. precalibrated pyrex columns. Except for these columns, all laboratory ware used was made of either platinum, Teflon, Vycor or quartz to minimize contamination of the type reported by Wasserburg, et al. (1964). The chemical dissolution and separation techniques are similar to those used by Gast (1962) and Compston, et al. (1965).

Total reagent and ion exchange procedure contamination blanks were determined for K, Rb and Sr. For a total chemical procedure involving reagents to process a 2 gm sample of meteorite and the ion exchange separation, the following contamination levels were found at La Jolla by repeated blanks: K = 0.75 μgm, Rb = 0.01 μgm, and Sr = 0.1 μgm. Contamination levels at Canberra are given by Compston, et al. (1965). In the case of the chondrules from the Peace River meteorite, contamination blanks were run side by side with the main experiment and the blanks determined. As expected, because of the much smaller amounts of reagents used and the ease with which the chondrules dissolved in the initial dissolution procedure, the blanks were lower and somewhat variable. In general, the percentage contamination correction for the chondrule analyses, both for Rb and Sr, were much higher than in the total meteorite analyses because of the small sample size of the chondrules. In Tables 5 and 6, the actual amounts of K, Rb and Sr in each sample analyzed and the percentage contamination correction applied are given.

In addition to the contamination that occurs in the chemical processing of the samples, cross contaminations in the mass spectrometer ion source is a possibility and stringent precautions were taken both in the mass spectrometric analyses of the isotope dilution runs as well as the isotopic composition determinations. In all cases, the Re-filaments of the triple filament source were prebaked at high temperatures inside the ion source until no trace of either Rb or Sr peaks were observed. Then these filaments were taken out and the samples were loaded on them. In all the Sr-isotopic analyses, the presence of isobaric contamination at mass 87 was checked by scanning the spectrum at mass 85 to look for Rb^{85}. None of the Sr-isotope analyses made at La Jolla contained any Rb contamination even on the most sensitive scale of detection, and those made at Canberra contained not more than 1 percent Rb^{87} in the total mass 87 beam.

The isotopic measurements reported here were performed on two different mass spectrometers. Three samples of Orgueil meteorite and two samples of Mokoia were analyzed in a Metropolitan-Vickers 6-inch radius, 90° mass spectrometer at the Australian National University. The general details concerning measurements made on this machine are reported elsewhere (Compston, Lovering and Vernon, 1965).

The rest of the samples were analyzed on a Nuclide Analysis Associates 12-inch radius, 60° mass spectrometer. Accelerating voltage of 5.5 kV was used. The ion source used multiple rhenium filaments, but in these analyses it was used as a double filament source, one on which the sample was loaded and the other used as an ionizing filament. The electron-multiplier collector was not employed, to avoid added mass discrimination. At operating ion currents of the order 10^{-12} to 10^{-13} amperes, the mass spectra were magnetically scanned repeatedly, and recorded on a strip chart recorder. An average analysis for isotopic composition consisted of about 15-30 such repeated scans of mass spectra. Repeat analyses of a standard Sr supplied by Professor Hurley, Massachusetts Institute of Technology, under these operating conditions have indicated that the Sr^{87}/Sr^{86} ratio can be measured accurately to 1 part in 700 at the 95 percent confidence level (Table 1).

It is well known now that significant mass fractionation occurs during Sr isotopic analysis. To correct for this, the observed Sr^{86}/Sr^{88} ratios are normalized to the measured Sr^{87}/Sr^{86} ratio. In this work, all Sr^{86}/Sr^{88} ratios have been normalized to 0.1194.

DATA AND DISCUSSION

1. Elemental Abundances

Elemental abundances of Rb, Sr and in some cases of K, have been determined along with the isotopic composition of Sr,for four separate chondrules, four carbonaceous chondrites and a hypersthene-olivine chondrite in this study. The carbonaceous chondrites chosen included members of all the three types, and the Peace River chondrite was chosen because it contained unusually large chondrules and was recovered very soon after its fall on March 31, 1962.

The K, Rb and Sr contents in four individual chondrules and the Peace River meteorite are given in Table 2. Duplicate analyses for the elemental abundances of K, Rb and Sr were done on Peace River meteorite by choosing two different pieces rather than splits of the same crushed sample. In the case of chondrules no duplicate analyses were possible for reasons of the sample size. The duplicate values of Rb given in Table 2, both of the chondrules and the Peace River Meteorite I do not represent duplicate independent determinations, but refer to separate mass spectrometric measurements of the same sample. The contents of both Rb and Sr in individual chondrules varies over a wide range and is perhaps controlled by the mineralogy of these chondrules. In contrast, duplicate analyses on the Peace River meteorite indicate a relatively homogeneous distribution of these elements. This appears to be true of the carbonaceous chondrites also, as indicated by the replicate analyses of some samples shown in Table 1.

The atomic abundances of K, Rb and Sr in carbonaceous chondrites relative to 10^6 atoms of Si are shown in Table 3. Variations of factors 2 to 3 occur in the alkali elements in the carbonaceous chondrites, the trend being a general decrease in abundance from Type I to Type III. These variations in K and Rb are in complete accord with variations noted for Na and K by Edwards and Urey (1955) and for the alkali elements by

Smales,et al. (1964), although the concentrations of K reported here for Orgueil, Murray and Mokoia are significantly lower than the values reported by Edwards and Urey (1955). In contrast to the marked variation shown by the alkali elements, Sr does not show such a variation. The uniformity of the high ages of all the three types of carbonaceous chondrites, discussed later in this paper, indicates that whatever mechanism caused this fractionation, whether a volatilization process or leaching and alteration, it must have occurred very early in the history of the solid matter that formed these meteorites.

2. Ages

The relevant data for age determination for all the samples analyzed in this study are listed in Table 7. Excellent discussions of the interpretation of an "age" measured by the Rb-Sr method are given by Gast (1962) and Anders (1962). Under the simple assumptions, 1) that at one time all the meteorites originally contained isotopically homogeneous Sr, and 2) that they have remained as closed systems since that time, it is possible to calculate an age for any given sample from the data in Table 7 by the standard Rb-Sr age equation,

$$(Sr^{87}/Sr^{86})_p = (Sr^{87}/Sr^{86})_o + Rb^{87}/Sr^{86} \ (e^{\lambda t}-1) \qquad (1)$$

if the value for $(Sr^{87}/Sr^{86})_o$ is known or assumed. In equation 1, the subscripts p and o refer to present day and initial times respectively, and λ is the decay constant of Rb^{87}. Ages thus obtained for the specific case where the $(Sr^{87}/Sr^{86})_o$ in a number of chondrites was similar to that observed now in several achondrites are the Model II ages of Gast (1962).

In the present study we require not only to measure the radiometric ages with an assumed $(Sr^{87}/Sr^{86})_o$ but also to explore the relationships between the initial strontium isotopic composition and the ages of the chondrules, chondrites and the carbonaceous chondrites. Consequently, the samples have been grouped in several different ways corresponding to different assumptions concerning their genesis, and the data for each group are examined by the isochron method. If the samples in any group fulfil Gast's Model I requirements (uniform $(Sr^{87}/Sr^{86})_o$ and chemical closure for the same subsequent time), then by equation 1, the relationship between (Sr^{87}/Sr^{86}) and Rb^{87}/Sr^{86} for such samples will be exact linear structure - the isochron - whose slope equals $(e^{\lambda t}-1)$ and whose intercept on the (Sr^{87}/Sr^{86}) axis equals $(Sr^{87}/Sr^{86})_o$. Thus on Model I assumptions, the scatter of the measured points about a straight line would be determined solely by experimental precision. It follows that these assumptions can be tested by comparing the observed variance of the points to the fitted line with prior or within-sample estimates of the experimental variance.

Unfortunately the statistical estimation of the isochron from the experimental data cannot be made in a completely satisfactory manner. There are significant errors of measurement in both (Sr^{87}/Sr^{86}) and Rb^{87}/Sr^{86}, so that a simple regression of (Sr^{87}/Sr^{86})against Rb^{87}/Sr^{86} is invalid. Moran (1956) shows that for such a case the slope of a linear structure will lie between limits set by the (true) regression lines of Y against X and of X against Y, these limits corresponding to values of o and oo for the ratio of the X- to Y- variances. Other treatments are available (e.g. Acton, 1959), but none (including Moran's) are strictly applicable to the Rb-Sr case owing to a further statistical complication. This is a probable non-homogeneous variance for Rb^{87}/Sr^{86} which arises from the isotope-dilution technique: if mass discrimination errors in measuring the Rb isotopic ratios are the sole source of error in this co-ordinate, then it may be predicted that the standard deviation for any value of Rb^{87} concentration will be a constant fraction of the value itself. Owing to these difficulties with statistical theory, not much confidence can be placed in the use of analysis of variance methods and statistical tests with these experimental data. We have attempted to allow for errors in both co-ordinates by first applying Moran's method of double regression to estimate limiting values for the slope of the isochron, and then adding the further uncertainty arising from the sampling errors in the two estimators.

Carbonaceous Chondrites

In recent years a number of detailed studies on this group of meteorites have led to some very interesting speculations on their origin. Urey (1961) has argued that carbonaceous chondrites were derived by alteration of high iron group of chondrites. The opposite point of view, that the carbonaceous chondrites, particularly Type I, represent primitive material aggregated from primordial solar nebula, has been adopted by Mason, (1960), Ringwood (1961), Wood (1962), and Anders (1964). Moreover, Mason and Ringwood have tried to derive the Types II and III from Type I, while Anders (1964) has suggested that all the three groups of carbonaceous chondrites represent varying mixtures of material condensed at high temperatures and material condensed at low temperatures. It was one of the objectives of the present study to see if there are any systematic age or $(Sr^{87}/Sr^{86})_o$ differences between the various groups of the carbonaceous chondrites, or between the carbonaceous chondrites and ordinary chondrites. If differences of this kind can be clearly demonstrated beyond experimental errors and outside of the resolution of Rb-Sr method of dating these objects, such evidence would have an unequivocal bearing on some of the hypotheses mentioned above.

The carbonaceous chondrites analyzed in this study include one sample from Type I (Orgueil), one from Type II (Murray), and two from Type III (Lance and Mokoia). The elemental concentrations are listed in Table 3 and the isotopic data are given in Table 7.

The carbonaceous chondrites as a whole form a well defined isochron with an age of 4.46 AE and a $(Sr^{87}/Sr^{86})_o$ of 0.7007 (Table 8). The two values for slope obtained by the double-regression differ by only 0.15 percent, which is negligible relative to the sampling errors in each regression. Following simple statistical theory (which may not strictly apply), the latter give rise to a 95 percent confidence interval of $\pm$ 0.35 AE, and in addition the standard deviations for $(Sr^{87}/Sr^{86})_p$ and

(Rb^{87}/Sr^{86}) variability may be roughly estimated as 0.0006 and 0.01 by analysis of variance. Both of these values are very close to estimates of measurement precision found from replicate analysis (Table 1). Thus all the variance in the fit of the data to the isochron appears to be accounted for by experimental error, implying that "geological error" is probably absent. In other words, the isochron assumptions of uniform $(Sr^{87}/Sr^{86})_o$ and subsequent chemical closure for the same time appear to be valid for these samples of carbonaceous chondrites, and thus no differentiation of the three types is evident from their Rb-Sr data considered in isolation. (It will be shown later that the inclusion of the achondrite value for initial Sr^{87}/Sr^{86} with this data qualifies this conclusion.)

It should be observed that the estimated standard deviation for replication of Rb^{87}/Sr^{86} is greater than expected solely from mass-discrimination error in determining Rb^{87}. The latter should be roughly 0.25 percent, which is almost a factor of 10 less than the observed (average) percentage standard deviation. This suggests that another source (or sources) of error may be present. If this is Sr contamination eluted from glassware (e.g. Wasserburg, et al. 1964) then the variance in Rb^{87}/Sr^{86} would now be homogeneous.

The mean value[I] 0.6985 has been found by Gast (1962) for Sr^{87}/Sr^{86} at the time of the (assumed) chondrite-achondrite fractionation, and by Pinson, et al. (1964) for the (assumed) common value for all chondrites. Following

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I normalized to Sr^{86}/Sr^{88} equal to 0.1194

Moran (1956), it is possible to test whether this value falls significantly outside the isochron limits for the carbonaceous chondrites, provided that the variance in Rb^{87}/Sr^{86} is homogeneous. The test shows that it does not, so that $(Sr^{87}/Sr^{86})_o$ for the carbonaceous chondrites may be the same in fact as for other meteorites, to within the present experimental resolution.

This possibility leads to other groupings of the analytical data of this paper: the regression lines may now be forced to pass through the point (0.6985, 0.000), and in addition the data for the Peace River meteorite may be included with the carbonaceous chondrites. The estimates for age corresponding to these groups are shown in Table 8.

Taking (0.6985, 0.000) as "known" for the carbonaceous chondrites, the isochron limits from double-regression are again very close together. The main uncertainty in the age is due as before to the sampling error of the estimators, but with some reduction produced by the increased range in Rb^{87}/Sr^{86}. The estimate for Sr^{87}/Sr^{86} variance based upon the residual sum-of-squares is now about eight times greater than the within-sample estimate. This would be very significantly greater using simple regression theory but as discussed earlier such a variance-ratio test is not strictly valid since there is error in both co-ordinates. The mean value for the age is increased by some 6 percent to 4.74 AE, which is in excellent agreement with the results of Gast (1962). The inclusion of the Peace River Meteorite data increases the mean value for age by about 2.5 percent for the carbonaceous chondrites alone, and gives 4.76 AE when the "known" point (0.6985, 0.000) is used.

Inspection of the isochron diagram (Figure 1) shows that most of the residual variance is contributed by the points for the Group III carbonaceous chondrites, Lance and Mokoia. An isochron forced through (0.6985, 0.000) will fit the remaining chondrites to within experimental error. This suggests that the data for the Group III carbonaceous chondrites may deviate significantly from the 0.6985 isochron owing to "geological error". One simple possibility would be their production from the Group I type some 0.3 AE after the main period of chondrite formation, corresponding to the 4.46 AE isochron presented by the carbonaceous chondrites alone. The latter isochron will possess time significance as a metamorphic isochron if Group III originated from Group I by Rb depletion. If the chondrite Murray (Group II) is regarded as a physical mixture of Group I and III then it also must lie on the metamorphic isochron joining the latter owing simply to material balance.

The age of the Orgueil meteorite obtained here has some topical importance. The discovery of "organized elements" in this meteorite and their possible biogenic nature has set off a great controversy regarding several aspects of terrestrial contamination of this meteorite (Anders, 1962). It must be pointed out that the Rb-Sr data of several samples of Orgueil indicate that with reference to this system, the meteorite has remained a closed system for some 4.7 AE. If terrestrial contamination occurred at all, it happened in such a way that the Rb-Sr system was not perturbed.

Peace River Chondrules

In view of the recent suggestions by Wood (1958, 1962) that chondrules represent droplets of silicates formed by direct condensation from the primitive solar nebula, it would be highly meaningful to attempt to measure both the ages of chondrules and their $(Sr^{87}/Sr^{86})_o$, directly and independently of other meteoritic data. The relationship of the initial Sr^{87}/Sr^{86} in chondrules to that of meteorites and their ages can provide information which bears upon their origin. For example, if chondrules were produced as in Wood's theory it is entirely possible that they contain a $(Sr^{87}/Sr^{86})_o$ that is even less radiogenic than that observed in achondrites, and their ages may be higher than that of meteorites. Conversely, if the chondrules were produced in some thermal event in the history of meteorite parent bodies after their accretion, their $(Sr^{87}/Sr^{86})_o$ may be more radiogenic than that of achondrites and their ages might be lower. Such an example for a meteorite has recently been reported (Compston, Lovering and Vernon, 1965). In all cases, the direction and magnitude of the change expected in the $(Sr^{87}/Sr^{86})_o$ depends upon the Rb-Sr ratio of the present system and the time interval.

Four chondrules from the Peace River meteorite, a hypersthene-olivine chondrite, have been studied here. These chondrules ranged in weight from 100 mg to 420 mg each, and they were found in an area of about 2" x 2" on a broken surface. All the chondrules showed radiating fibrous structures to the naked eye, were spheroidal or ellipsoidal in shape, and were easily distinguishable from the fine-grained matrix. The Rb, Sr and K elemental abundances are given in Table 2 and the isotopic data in Table 7.

In these four chondrules, although the Rb and Sr contents varied by several factors, unfortunately the Rb/Sr ratios did not vary over a wide enough range to define a precise isochron. Furthermore, the scatter among the chondrule data (Figure 1) is much greater than expected on previously-used estimates of experimental errors. The reason for this scatter may be due to failure of the basic assumptions that all chondrules are of the same age and contained the same $(Sr^{87}/Sr^{86})_o$, and that each of the chondrules has remained a closed system since the time of its formation. The Peace River meteorite is a metamorphosed hypersthene-olivine chondrite of the low-iron group, and it is entirely reasonable to think that at the levels of the chondrule dimensions, Rb and Sr may be labile during the lifetime of these chondrules in this meteorite. In addition, part of the scatter of the chondrule points may be due to greater experimental uncertainties in the measurement of their Rb/Sr ratios arising from the much smaller amounts of Rb and Sr handled during analysis.

Comparison with the lead meteoritic isochron

The age calculated by Patterson (1955) for the time of the U-Pb fractionation and chemical closure of certain meteorites is extremely precise owing to the demagnification of experimental error which occurs during the use of the Pb-Pb age equation. His quoted uncertainty of $\pm$ 0.07 x 10^9 years is in fact close to the 95 percent confidence limits despite the few samples analyzed. Thus Patterson's maximum value for age, 4.62 x 10^9 years, is just below the minimum Rb-Sr value for the combined chondrite data (Table 8) forced to pass through 0.6985 as $(Sr^{87}/Sr^{86})_o$.

No other grouping of the data in this paper suggests a significant difference, but the mean age values of Gast (1962) and Pinson, et al. (1964) are similarly greater than 4.55×10^9 years.

It is tempting to remove this apparent discrepancy with the lead age by an increase in the value of the Rb^{87} decay constant used so far in this paper, 1.39×10^{-11} year. Such an adjustment would employ the assumptions i) that the U-Pb fractionation during meteorite evolution occurred at closely the same time as the Rb-Sr fractionation and ii) that all the particular meteorites analyzed evolved at the same time and have since remained chemically closed. It seems to the authors more desirable on the contrary to endeavour to test these assumptions using an independent comparison of results obtained by the two techniques. Furthermore it must be remembered that the particular value used for the Rb^{87} decay constant is already the result of comparitive U-Pb and Rb-Sr geochronology (Aldrich, et al. 1956), using samples which are at least as likely as meteorites considered as a group to be cogenetic and coeval. Independent modern determinations of λ Rb^{87} by different physical methods are of no help, since they are discouragingly scattered (Leutz, et al. 1962), and no objective means is evident of selecting which of these is correct (if any).

We conclude that the correlation of the Pb with Rb-Sr work on meteorites must remain an open question. It is possible that the Pb isochron of Patterson (1955) represents the most accurate measurement of an age of general chemical fractionation of meteoritic material which includes the carbonaceous chondrites, or it is possible that the Pb isochron refers to a slightly younger event in meteoritic evolution to which the Group III carbonaceous chondrites may belong, but with Group I being slightly older.

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TABLE 1. Reproducibility of Sr and Rb isotopic measurements

A. Replicate Sr^{87}/Sr^{86} Analyses of M.I.T. Eimer and Amend Reagent Standard Sr.

No	Date La Jolla	Sr^{87}/Sr^{86}	$(Sr^{87}/Sr^{86})corr.$	Sr^{86}/Sr^{88}
1	July 11, 1963	0.705	0.707	0.1201
2	July 12, 1963	0.705	0.707	0.1201
3	July 12, 1963	0.706	0.708	0.1200
4	July 16, 1963	0.706	0.708	0.1203
5	July 19, 1963	0.705	0.708	0.1202
*6	July 21, 1963	0.704	0.707	0.1204
*7	July 22, 1963	0.705	0.707	0.1200
*8	July 22, 1963	0.706	0.708	0.1201
*9	July 23, 1963	0.705	0.707	0.1201
*10	July 24, 1963	0.707	0.708	0.1200
	Average		0.7075	0.1201
	Standard deviation		± 0.0005	0.00013

$(87/86)_{corrected}$ by normalizing observed 86/88 to 0.1194 and applying half of this correction to observed 87/86. For the other measurement an electron multiplier was used and a square root of mass ratio correction applied for all the observed values.

B. Replicate Sr^{87}/Sr^{86} analyses of meteorites (see later Tables)

Orgueil I	0.7437
	0.7444
	0.7435
	0.7435
	0.7436
	0.7429

* Ion detection by straight collector

TABLE 1 (Cont'd)

Mokoia	0.7144
	0.7146
Peace River Chondrule II	0.7400
	0.7394
	0.7471
IV	0.7473
Standard deviation from pooled variance	: 0.0004

C. Replicate Rb^{87}/Sr^{86} analyses of meteorites (see later Tables)

Orgueil I	0.677
	0.651
Mokoia	0.215_2
	0.213_5
**Bishopville I	0.482
	0.469
**Bishopville II	0.393
	0.379
Standard deviation from pooled variance	: 0.009

TABLE 2. Concentrations of K, Rb and Sr in Peace River Meteorite and its Chondrules.

Sample	K (ppm)	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}
Chondrule I	---	4.90	17.61	0.787
Chondrule II	---	1.40 1.42	5.79	0.686
Chondrule III	718	1.42	8.41	0.478
Chondrule IV	---	4.16 4.16	17.92	0.656
Peace River Total Meteorite I	765	2.64 2.59	10.25	0.720
Peace River Total Meteorite II	752	2.46	9.82	0.709

TABLE 3. Concentrations of K, Rb and Sr in Carbonaceous Chondrites.

Sample		K (ppm)	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}
Type I					
Orgueil	I A	347	1.78	7.73	0.650
	I B	343	1.76	8.18	0.608
	I C	345	1.74	7.77	0.633
Orgueil	II	494	2.08	8.74	0.671
Type II					
Murray		266	1.57	9.38	0.473
Type III					
Mokoia	A	311	1.20	16.23	0.215
	B	335	1.21	16.28	0.214
Lance		388	1.42	14.65	0.274

TABLE 4. Atomic abundances of K, Rb and Sr relative 10^6 atoms of Si in carbonaceous chondrites.

	K	Rb	Sr
Type I	36 ± 4	6.5 ± 0.6	24 ± 1
Type II	25 ± 5	4.1 ± 0.2	25 ± 1
Type III	18 ± 2	2.6 ± 0.2	31 ± 2
Chondrites	34 ± 4	4.4 ± 1.1	20 ± 1

TABLE 5. Contamination corrections for potassium and rubidium analyses

Sample			K Concentration in sample ugm/gm	Sample K processed ugms	Contamination correction %	Rb Concentration in sample ugm/gm	Sample Rb processed ugms	Contamination correction %	K/Rb
Peace River Chondrule	I		---	---	---	4.90	1.54	0.6	
	II		---	---	---	1.41	0.18	5.5	
	III		718	105	0.7	1.42	0.21	9.5	506
	IV		---	---	---	4.16	1.29	0.8	
Peace River Meteorite	Total I		756	325	0.2	2.62	1.12	0.9	292
	II		752	1567	0.05	2.46	5.14	0.2	306
Orgueil	I	A	347	176	2.9	1.78	0.90	1.4	195
		B	343	154	3.2	1.76	0.79	1.4	195
		C	340	318	1.4	1.75	1.60	0.7	198
	II		494	427	0.18	2.08	1.79	0.6	237
Murray			266	218	0.34	1.57	1.29	1.5	169
Mokoia		A	311	156	3.2	1.20	0.60	1.9	259
		B	335	190	2.7	1.21	0.74	1.5	277
Lance			388	249	0.30	1.42	0.91	1.1	273

TABLE 6. Contamination corrections for Sr analyses

Sample			Sr Concentration ugm/gm	Sample Sr Processed ugms	Contamination correction %
Peace River Chondrule	I		17.61	5.51	1.8
	II		5.79	.75	6.7
	III		8.41	1.07	9.3
	IV		17.92	5.56	1.8
Peace River Total Meteorite	I		10.25	4.36	4.6
	II		9.82	20.49	0.5
Orgueil	I	A	7.73	3.91	2.1
		B	8.18	3.49	2.4
		C	7.77	7.13	1.1
Orgueil	II		8.74	7.55	1.3
Murray			9.38	7.72	1.3
Mokoia		A	16.23	8.12	1.1
		B	16.28	9.90	0.8
Lance			14.65	9.36	1.1

TABLE 7. Isotopic composition of Sr in chondrules and carbonaceous chondrites

Sample	Rb^{87}/Sr^{86}	$(Sr^{87}/Sr^{86})_{Meas.}$	$(Sr^{86}/Sr^{88})_{Meas.}$	$(Sr^{87}/Sr^{86})_{Corr.}$
Peace River Chondrule I	0.787	0.7479	0.1194	0.7478
Chondrule II	0.686	0.7395	0.1195	0.7400
		0.7388	0.1196	0.7394
Chondrule III	0.478	0.7198	0.1217	0.7267
Chondrule IV	0.656	0.7469	0.1194	0.7471
		0.7468	0.1195	0.7473
Peace River Total Meteorite I	0.720	0.7560	0.1171	0.7488
Peace River Total Meteorite II	0.709	0.7442	0.1202	0.7467
Orgueil I A	0.650	0.7433	0.1197	0.7444
		0.7429	0.1196	0.7437
I B	(0.608)	0.7423	0.1198	0.7435
		0.7420	0.1199	0.7435
I C	0.633	---	---	0.7436*
				0.7429*
Orgueil II	0.671	0.7419	0.1200	0.7435
Murray	0.473	0.7280	0.1201	0.7300
Mokoia A	0.2154	(0.712 ± 0.001)	0.1197	(0.7129)
B	0.2135	0.7130	0.1200	0.7146
		0.7128	0.1199	0.7144
Lance	0.274	0.7189	0.1193	0.7185

(Sr^{87}/Sr^{86}) corrected by normalization to $Sr^{86}/Sr^{88} = 0.1194$

* Values obtained by use of a double tracer to correct for fractionation.

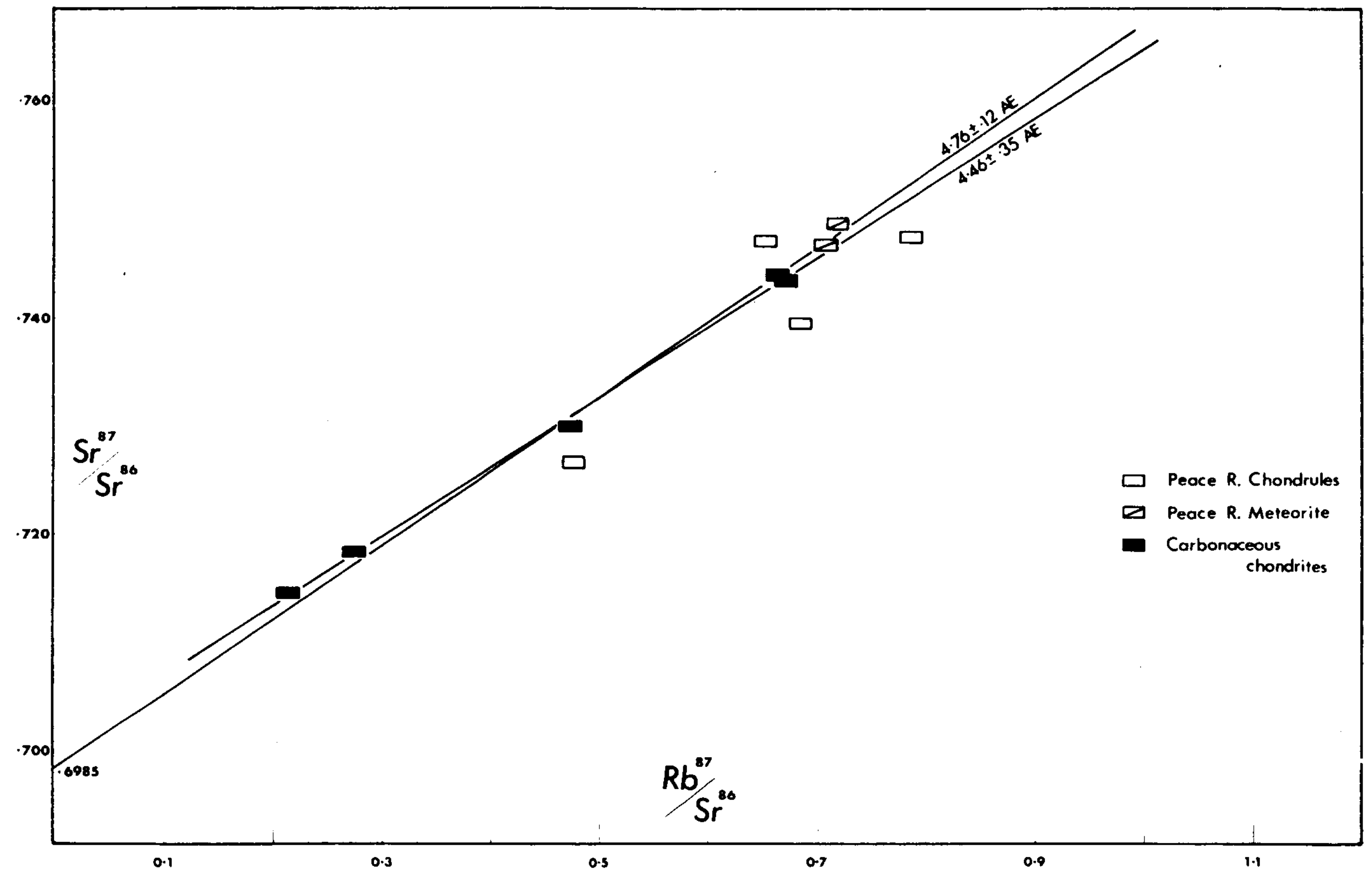
TABLE 8. Rb-Sr ages as given by different meteorite groupings

Group of Samples	$(Sr^{87}/Sr^{86})_o$ calculated	$(Sr^{87}/Sr^{86})_o$ assumed	Slope	*Age(10^9 years)
Carbonaceous chondrites	0.7007	---	(0.0639 ((0.0640	4.46 ± 0.35
	---	0.6985	(0.06806 ((0.06812	4.74 ± 0.21
Carbonaceous chondrites and Peace River meteorite	0.7001	---	(0.06559 ((0.06582	4.58 ± 0.32
	---	0.6985	(0.06839 ((0.06843	4.76 ± 0.12
Peace River chondrules	---	0.6985	(.0642 ((.0647	4.5 ± 0.8

* The uncertainty shown is the 95 percent confidence limit, and the value used for λ Rb^{87} is 1.39×10^{-11} year.

LEGEND FOR FIGURE

Figure 1: Rb-Sr isochrons for carbonaceous chondrites alone, and for the Peace River and carbonaceous chondrites with assumed initial Sr^{87}/Sr^{86} of 0.6985.



4·76 ± ·12 AE
4·46 ± ·35 AE
·760
·740
·720
·700
·6985
Sr87/Sr86
Rb87/Sr86
0·1
0·3
0·5
0·7
0·9
1·1
Peace R. Chondrules
Peace R. Meteorite
Carbonaceous chondrites