Precise Determination of the Age of Formation of Meteorites

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1. Introduction

Meteorites have been considered to correspond to fragments of planetesimals or planets formed at the early stage of the solar system. Chronological data on meteorites should give us significantly important information on the time-scale for the early history of the solar system, especially on the early evolution and differentiation of planets or planetesimals. Chronological data also give us the chemical information, since the isotope evolution of the radiogenic nuclide may reflect the chemical differentiation which the parent body had undergone. It has been generally believed that the age of the earth and solar system should be around $4.5 \sim 4.6 \times 10^9$ yrs. One of the most convincing reasons is that most of the chondritic meteorites (not all) give the age around $4.5 \times 10^9$ yrs and few meteorites have a significantly older age than $4.5 \times 10^9$ yrs by any chronological method.

On the other hand, some meteorites of a younger age than $4.5 \times 10^9$ yrs have been found. In many cases, these young ages can be attributed to the redistribution of elements or mixing of different kinds of rocks caused by shock or brecciation events. The early differentiation on the parent bodies would have occurred soon after their formation and this differentiation has been considered to continue for a short period. So most achondritic meteorites have been regarded to have their original formation age around
4.5 \times 10^9 \text{ yrs.} \text{ However, recent progress in dating technique enables us to determine the age with a high precision and to analyze the small difference between different types of achondrites. Such study can give a new impact on the hypothesis for the achondrite evolution system. In this section, we present the chronological studies on several differentiated meteorites as follows;}

(a) diogenites, belonging to the HED (howardite eucrite and diogenite) association.

(b) lunar meteorites, derived from moon; they are also young meteorites.

We also show REE (rare earth elements) abundance patterns to discuss the genesis of these meteorites. In addition, recent studies on other young meteorites will be introduced.

2. Isotope systematics and method of measurements

There are several isotope systems for chronology, \textit{i.e.}, long-lived radioactive isotopes and their stable daughter products. $^{40}\text{K}$-$^{40}\text{Ar}$, $^{87}\text{Rb}$-$^{87}\text{Sr}$, $^{147}\text{Sm}$-$^{143}\text{Nd}$, and U-Pb isotope systems are commonly used to date the crystallization event for silicate samples. In the studies mentioned in this paper, the $^{87}\text{Rb}$-$^{87}\text{Sr}$ system was mainly used. Meteorites, needless to say, are a very precious sample, but a certain amount of the sample is required to measure the isotope ratio and the parent-daughter atomic ratio with high precision. Generally, Sr abundance is higher than Nd or Pb in meteorites. Therefore, the Rb-Sr isotope system has been usually first applied to the dating of meteorites. For example, some diogenites, as shown in the next section, contain less than 0.07 ppm of Sr and less than 0.006 ppm of Nd. In order to determine the isotope ratios precisely (analytical errors are around 10 \sim 20 \text{ ppm}), about 50 ng of Sr or Nd is needed, and more than 700 mg of diogenites will be necessary for Sr measurements and more than 8 g for the Nd measurements.

In the study presented in this paper, a Ta single filament system was used with phosphoric acid for mass spectrometry to measure the Sr isotope ratios, and for the $^{87}\text{Rb}/^{86}\text{Sr}$ atomic ratios, a Re single filament (for Rb abundances) and a Ta-Re-Ta triple filament (for Sr abundances) were used. In a recent study, a W or Re filament system with $\text{Ta}_2\text{O}_5$ and phosphoric acid was also used to measure the Sr isotope ratios. In this work, Sr isotope
ratios were measured with a VG-354 multi collector system and the abundance of Sr, Rb, and REE were determined by the isotope-dilution method using a JEOL JMS-05RB mass spectrometer.

3. Ages of some diogenites and their genetic implications

The achondritic meteorites known as eucrites and diogenites are igneous rock and have been considered to derive from the crust and the mantle, respectively, of a common parent planet or asteroid (Mason, 1967; Clayton et al., 1976). Several eucrites have been dated 4.5 \(\sim\) 4.6 \(\times\) 10\(^9\) yrs by the Rb-Sr method (e.g., Allegre et al., 1975). On the other hand, a Rb-Sr age of 4.45 \(\pm\) 0.18 \(\times\) 10\(^9\) yrs has been reported for three diogenites by Birck and Allegre (1981). From these data, one cannot judge whether diogenites and eucrites have the same age or not. We succeeded in presenting precise Rb-Sr data for several diogenites (Tatahouine, Johnstown, Roda, and Yamato-791422) and one eucrite (Juvinas) to discuss their mutual genetic relationship. Here we consider only the dates obtained by the Rb-Sr method to discuss the relative ages of the meteorites irrespective of the accuracy of the decay constant of the parent nuclide.

The \(^{87}\text{Rb}^{87}\text{Sr}\) analytical data and the results of dating are shown in Tables I and II, respectively. As shown in Table I, diogenites are very poor in Rb and Sr. Total blanks of Rb and Sr for treatment of 500-900 mg samples were 0.008 and 0.015 ng, respectively, and because they never exceeded 0.05% of the sample values, we did not make blank corrections.

The Johnstown diogenite consists of coarse-grained clasts (cm-sized) and brecciated matrix. According to electron-probe microanalysis with JCXA-733, the coarse-grained clasts were orthopyroxene (opx; En\(_{73-74}\) Fs\(_{23-24}\)) and the brecciated matrix contains mainly fragments of orthopyroxene, the composition of which is in the same range as that of the clasts. We analyzed 4 samples from Johnstown; one sample containing several clasts and three samples from the brecciated portion. The Juvinas eucrite was separated into three fractions with heavy liquids (acetone, bromoform and methylene iodide saturated with iodoform).

As shown in Table II, the eight diogenite samples (four from Tatahouine and four from Johnstown) define an age of 4.394 \(\pm\) 0.011 \(\times\) 10\(^9\) yrs with quite a small uncertainty. The isochron for these samples is shown in Fig. 1. It is
Table I. Rb-Sr analytical data

<table>
<thead>
<tr>
<th>Sample name</th>
<th>amount (mg)</th>
<th>Sr (ppm)</th>
<th>Rb (ppm)</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr}(\pm 2\sigma))</th>
<th>(^{87}\text{Rb}/^{86}\text{Sr}) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Juvinas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>whole rock</td>
<td>18.61</td>
<td>69.01</td>
<td>0.0965</td>
<td>0.699229 ± 16</td>
<td>0.00404</td>
</tr>
<tr>
<td>#1 suspension</td>
<td>21.54</td>
<td>90.51</td>
<td>0.2262</td>
<td>0.699453 ± 16</td>
<td>0.00740</td>
</tr>
<tr>
<td>d&lt;2.9 g/cm³</td>
<td>15.07</td>
<td>168.97</td>
<td>0.1172</td>
<td>0.699094 ± 20</td>
<td>0.00201</td>
</tr>
<tr>
<td>d&gt;3.3 g/cm³</td>
<td>38.92</td>
<td>14.37</td>
<td>0.0900</td>
<td>0.700161 ± 24</td>
<td>0.01811</td>
</tr>
<tr>
<td>#2Johnstown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opx clasts</td>
<td>180.24</td>
<td>0.4250</td>
<td>0.01932</td>
<td>0.707421 ± 28</td>
<td>0.1314</td>
</tr>
<tr>
<td>matrix 1</td>
<td>98.66</td>
<td>2.773</td>
<td>0.02152</td>
<td>0.700395 ± 36</td>
<td>0.02243</td>
</tr>
<tr>
<td>matrix 2</td>
<td>99.71</td>
<td>2.707</td>
<td>0.02183</td>
<td>0.700460 ± 24</td>
<td>0.02327</td>
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<tr>
<td>matrix 3</td>
<td>95.83</td>
<td>2.129</td>
<td>0.02642</td>
<td>0.701275 ± 20</td>
<td>0.03588</td>
</tr>
<tr>
<td>#3Tatahouine1</td>
<td>803.54</td>
<td>0.06190</td>
<td>0.02614</td>
<td>0.778255 ± 16</td>
<td>1.2301</td>
</tr>
<tr>
<td>#3Tatahouine2</td>
<td>750.76</td>
<td>0.06081</td>
<td>0.02570</td>
<td>0.778226 ± 36</td>
<td>1.2310</td>
</tr>
<tr>
<td>#4Tatahouine3</td>
<td>791.39</td>
<td>0.07546</td>
<td>0.01035</td>
<td>0.724603 ± 40</td>
<td>0.3973</td>
</tr>
<tr>
<td>#4Tatahouine4</td>
<td>900.58</td>
<td>0.07682</td>
<td>0.01062</td>
<td>0.724658 ± 40</td>
<td>0.4005</td>
</tr>
<tr>
<td>#5Roda</td>
<td>46.47</td>
<td>6.086</td>
<td>0.04514</td>
<td>0.700418 ± 24</td>
<td>0.02144</td>
</tr>
<tr>
<td>Y-791422</td>
<td>96.41</td>
<td>13.434</td>
<td>0.08370</td>
<td>0.700176 ± 20</td>
<td>0.01801</td>
</tr>
<tr>
<td>NBS 987</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.710195 ± 20</td>
<td>-</td>
</tr>
</tbody>
</table>

*Uncertainties are less than 0.5%.

#1 Suspension (Juvinas) is the fraction which is suspended in aceton.

#2 Johnstown; AMNH #2497.

#3 Tatahouine-1, -2; No. 1644.

#4 Tatahouine-3, -4; Me 2651.

#5 Roda; #640.

Notable that the data of Tatahouine-1 and -2 are very close to each other, whereas the data of Tatahouine-3 and -4 are also mutually very close, but fall in the diagram far from those obtained for Tatahouine-1 and -2. Also, it can be seen that the positions for the Johnstown samples are far from those for the Tatahouine samples, but form an isochron not only among themselves but also in concordance with the Tatahouine data. An age of 4.394 ± 0.011 × 10⁹ yrs has been obtained from the isochron including Tatahouine and Johnstown; the small uncertainty is noteworthy. In the diagram, the dotted line is the isochron for the Juvinas eucrite corresponding to the age of 4.52 × 10⁹ yrs. The age of Juvinas has an uncertainty of 0.15 × 10⁹ yrs (see Table II) so that the lower limit is Juvinas is 4.37 × 10⁹ yrs. As
Table II. The results of dating

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>ISr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatahouine (4 samples)</td>
<td>4.398 ±0.028 b.y.</td>
<td>0.69895 ±4</td>
</tr>
<tr>
<td>Johnstown (4 samples)</td>
<td>4.390 ±0.035 b.y.</td>
<td>0.69897 ±4</td>
</tr>
<tr>
<td>Tatahouine + Johnstown (8 samples)</td>
<td>4.394 ±0.011 b.y.</td>
<td>0.69896 ±2</td>
</tr>
<tr>
<td>Roda</td>
<td>4.63 ±0.08 b.y.</td>
<td>*</td>
</tr>
<tr>
<td>Y-791422</td>
<td>4.60 ±0.07 b.y.</td>
<td>*</td>
</tr>
<tr>
<td>Juvinas</td>
<td>4.52 ±0.15 b.y.</td>
<td>0.69896 ±2</td>
</tr>
</tbody>
</table>

*The ages for Roda and Y-791422 were calculated from their whole rock data and the initial ratio of Juvinas, 0.69896.

Previous workers (Allegre et al., 1975; Nyquist et al., 1986) reported, the ages obtained for Juvinas or other typical eucrites are 4.51 ~ 4.54 × 10^9 yrs (errors were 0.04 ~ 0.05 × 10^9 yrs) and there is little probability that the age of Juvinas is 4.37 ~ 4.39 × 10^9 yrs. The ages of Tatahouine and Johnstown, 4.39 (upper limit is 4.40) × 10^9 yrs, can be recognized as distinctly younger than the age of eucrites. Birck and Allegre (1978) reported that Tatahouine was disturbed for Rb-Sr system on a small distance scale. It is not considered that our results reflect such a disturbance, because our measurements were done for larger scale, i.e., for samples weighing about 1g, and the data on the fragments from same chip are in very good agreement with each other. On the other hand, the Rb-Sr data for Roda and Yamato-791422 fall near the 4.52 × 10^9 yrs reference isochron for eucrite, as shown in Table II. Y-791422 is classified as a Y-75032-type diogenite. This group of diogenites has been recognized as a unique type of diogenites, which have relatively Ca-rich compositions compared with other typical diogenites, and they are considered to have a close relationship with eucrites, based on mineralogical and chemical characteristics (Takeda and Mori, 1981). These observations on Rb-Sr systematics suggest that diogenites would be roughly divided into two groups. The first group, to which Tatahouine and Johnstown belong, has younger age than eucrites and the other group, to which Roda and Y-75032 type diogenites belong, has the Rb-Sr data close to eucrites. Concerning young age of Johnstown and Tatahouine, one interpretation is that this age reflects secondary metamorphism (e.g., shock) or evolution process branching from that for other diogenites (e.g., Roda or Y-75032 type). And another one is that Tatahouine and Johnstown are genetically distinct from some diogenites (Roda or Y-75032 type) and from the eucrites. As
Fig. 1. The isochron plot for diogenites. The narrow triangular area at the lower left is shown magnified in the upper left. The data for fragments from the same chip (Tatahouine-1,-2,-3 and -4) are too be close to distinguished on this plot (Opx; orthopyroxene). The inset on the right-hand side shows the relative deviation ($\times 10^{-4}$) from the best-fit-line age of $4.394 \times 10^9$ yrs ($\tau = 0.69896$) as a function of $^{87}$Rb/$^{86}$Sr.

$$\epsilon = \frac{({^{87}}\text{Sr}/^{86}\text{Sr})_{\text{meas.}} - ({^{87}}\text{Sr}/^{86}\text{Sr})_{\text{calc.}}}{({^{87}}\text{Sr}/^{86}\text{Sr})_{\text{calc.}}} \times 10^4$$
discussed later, we prefer the latter interpretation based on REE patterns and $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio data.

The REE patterns are shown in Fig. 2. The REE patterns of Roda and Y-791422, which give the age of $4.51 \times 10^9$ yrs, are higher than those of Tatahouine and Johnstown and are similar to the pattern of the pyroxene fraction of the Juvinas eucrite, whereas the REE patterns of Tatahouine and Johnstown, which give the age of $4.394 \times 10^9$ yrs, have some unique characteristics, especially the concave curvature between La and Sm. Although the REE patterns for matrix samples of Johnstown appear rather similar to those of Roda, the Johnstown samples are distinguished from Roda on the Rb-Sr isochron-plot. These observations on the REE patterns do not favor a simple formation model for diogenites, as Consolmagno (1979) discussed, assuming that REE partition coefficients for Opx do not vary appreciably with such conditions of formation as cooling rate, temperature and/or chemical composition.

As discussed above, regarding the age and the characteristics of REE pattern, it is possible that Tatahouine and Johnstown are genetically different from the eucrite group and a group of some unique diogenites (Roda and Y-75032 type). This speculation is supported by the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of the isochron for Johnstown and Tatahouine. If the ages of Johnstown and Tatahouine would indicate the age of secondary metamorphism, the isochrons of $4.394 \times 10^9$ yrs and $4.52 \times 10^9$ yrs, should cross each other around the data point of Roda or Y-791422 in Fig. 1. As shown in Fig. 1, these two isochrons cross near the $^{87}\text{Sr}/^{86}\text{Sr}$-axis. Namely, initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of these isochrons are close to each other and are the same within the error limits. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ value observed for the $4.39 \times 10^9$ yrs isochron is $0.69896 \pm 0.00002$ and the corresponding value actually observed for the $4.52 \times 10^9$ yrs isochron is also $0.69896 \pm 0.00002$. The increase of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the parental material should have been less than $0.00002-0.00004$ during about one hundred million years. Thus, Tatahouine and Johnstown were formed from the material with a lower Rb/Sr abundance ratio than 0.004, corresponding to an increase of 0.00002 for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio during one hundred million years. In diogenitic materials, Rb/Sr abundance ratios are higher than about 0.006 (for an example, 0.0064 in Y-791422) and Roda, Y-791422 or other such diogenitic materials can not be the parent material. The parent material of basaltic acon-
Fig. 2. The REE patterns of Tatahouine and Johnstown-opx are characterized by curvature between La and Sm. Such curvature has not been found in the REE patterns of the pyroxene fractions of eucrite.
drites is considered to have low Rb/Sr abundance ratio \((^{87}\text{Rb}/^{86}\text{Sr} < 0.01;\) this corresponds to Rb/Sr < 0.0037), as discussed by some workers (Birck and Allegre, 1978; Papanastassiou and Wasserburg, 1969). One possibility is that there still remained parent material with such low Rb/Sr ratio, after the primary formation of eucrites and some of diogenites (Roda or Y-75032 type), and magmatic differentiation took place at a certain period (\(1 \times 10^8\) yrs later than formation of eucrites and unique diogenites) in deep layer of the parent body to produce the diogenites like Johnstown or Tatahouine and possibly some of young cumulate type eucrites like Sioux County (Birck and Allegre, 1978). For this eucrite, its age is \(4.19 \pm 0.14 \times 10^9\) yrs \((\lambda = 1.39 \times 10^{-11}/\text{yrs} \) was used for the calculation), which corresponds to \(4.10 \times 10^9\) yrs if \(\lambda = 1.42 \times 10^{-11}/\text{yrs}\) is used, and the initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio seems low, 0.69897 ± 8. Besides, regarding REE patterns, there still remains a doubt about the genetically close relationship between the young diogenites, such as Johnstown or Tatahouine, and eucrites. And the data obtained here is open to the possibility that eucrites as represented by Juvinas and diogenites like Johnstown and Tatahouine came from different parent bodies. However, it is difficult to point out the candidates which can be a complementary material for these “young” diogenites.

In conclusion, we consider that the diogenites like Johnstown and Tatahouine were formed by a distinct process from that of the achondrites like Roda or Y-75032 and that their formation occurred about one hundred million years after the formation of typical eucrites. We also consider that the diogenite parent body kept some igneous activity for about one hundred million years after its formation.

4. Young age of glassy material from a Lunar meteorite

Since 1969, more than several thousand of meteorites have been recovered from the Antarctic. Of these “Antarctic meteorites”, some are recognized to belong to a rare or unique type. Lunar meteorite is one of these unique meteorite types discovered only in Antarctica. According to chemical, petrological and mineralogical study (e.g., Abstract the 11th symposium on Antarctic meteorites, 1985), most of “Lunar meteorites” have been known to have originated from lunar highlands. It is believed that the lunar highlands were formed at the earliest stage, about \(4.4 \sim 4.5 \times 10^9\) yrs
ago, and believed to have undergone intense bombardment around $4.0 \times 10^9$ yrs ago (Basaltic Volcanism on the Terrestrial Planets, 1981). Therefore, most of the isotopic systems of the highland samples, including lunar meteorites, were reset by the brecciation, shock metamorphism, and/or partial or complete melting and the ages cluster around $4.0 \times 10^9$ yrs. As shown in Fig. 3, the age obtained for Yamato-791197 (one of the lunar meteorites) is $3.89 \times 10^9$ yrs.

Even from the intense bombardment $4.0 \times 10^9$ yrs ago, a collision of planetesimals has continued intermittently until the present. The collision of a planetesimal on a planet produces the crater on the planets, and at the same time a partial or completely melting event should be induced on and around the collision spot. The chronological studies of these remelted samples should give the age of impact and the information about crater formation on planets and satellites.

Yamato-82192 is one of the lunar meteorites considered to come from the lunar highlands. Many fragments of this meteorite show the age of $3.9 \times 10^9$ yrs (Takahashi and Masuda, 1987). However, one fragment of Yamato-82192, SubNo.63B, shows a remelted feature distinct to other common lunar meteorite samples characterized as anorthosite breccia. This glassy lithology

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![Figure 3: The Rb-Sr isochron diagram of Y-791197 SubNo. 108. The inset on the right-hand side is the same as that in Fig. 1.](image)

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Age = $3.89 \pm 0.36 (2\sigma)$ b.y.
Initial = $0.69894 \pm 4$
is considered to have been produced by the impact melting. A younger age than $3.9 \times 10^9$ yrs was expected for this sample. Here we present the result for $^{87}\text{Rb}-^{87}\text{Sr}$ dating of this impact-melted portion.

A small part (5mg) of this chip was used for the analysis of a whole rock sample and the remaining part ($\sim 60$mg) was crushed and separated into some fractions with heavy liquids (methyleneiodide and bromoform) and the analyses of Rb-Sr system were carried out on each fraction (The fraction suspended in acetone is called “suspension” here). Sr isotope ratios were measured with VG-354 mass spectrometer and the abundances of Sr and Rb were analyzed by the isotope dilution method, using mass spectrometer (JEOL JMS-05RB). The results are shown in Table III. The errors for abundances are within 0.5%. Based on the analyses of the major element compositions by EPMA (JEOL JXA-733), the fractions with densities lower than 3.25 g/cm$^3$ are composed chiefly of Ca-rich plagioclase or Ca, Al-rich glass. The fraction with the highest density (higher than 3.25 g/cm$^3$) is composed of olivine with small amount of pyroxene.

Figure 4 shows the REE patterns of the samples obtained from Y-82192. Y-82192 SubNo.63B is the glassy sample as mentioned above and SubNo.55A is one of the samples characterized as anorthositic breccia. As shown in Fig. 4, the REE abundances in this melted sample remained unchanged irrespective of melting. On the other hand, as shown in Fig. 5, the Rb-Sr system was significantly disturbed by the melting, although the whole rock sample of Y-82192, SubNo.63B, lies near the $3.95 \times 10^9$ yrs line defined by some unmelted samples of lunar meteorites (see the solid line in Fig. 5; the data of the solid line are from our study, Takahashi and Masuda, 1987). Among the separated fractions plus the whole rock under consideration, five (four fractions with the densities lower than 3.25 and the whole rock sample) fall nearly on a line and other two fractions (suspension and a fraction with density higher than 3.25) lie at distinct positions. Taking into account the melting temperature, it is considered that the fraction, $d > 3.25$g/cm$^3$, chiefly of olivine might have been more resistive to a melting process than other fractions composed chiefly of plagioclase and glass, and an isotopic homogenization was not completed for the olivine fraction. Besides, the deviation of the point for the suspension fraction is considered to suggest that the material constituting this fraction is different in origin from the main part of the whole rock. For materials whose densities
Table III. Rb-Sr systematics for samples from Y-82192, SubNo.63B.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>amount (mg)</th>
<th>Sr (ppm)</th>
<th>Rb (ppm)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ ($\pm 2\sigma$)</th>
<th>$^{87}\text{Rb}/^{86}\text{Sr}$</th>
<th>Model age (m.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>whole rock</td>
<td>4.32</td>
<td>143.9</td>
<td>0.390</td>
<td>0.699572 +22</td>
<td>0.00783</td>
<td>734 +95</td>
</tr>
<tr>
<td>suspension</td>
<td>10.90</td>
<td>140.1</td>
<td>0.439</td>
<td>0.699614 +16</td>
<td>0.00907</td>
<td>-</td>
</tr>
<tr>
<td>d&lt;2.75 g/cm$^3$</td>
<td>2.51</td>
<td>115.9</td>
<td>0.978</td>
<td>0.699635 +24</td>
<td>0.0244</td>
<td>704 +69</td>
</tr>
<tr>
<td>2.75&lt;d&lt;2.9</td>
<td>2.15</td>
<td>145.7</td>
<td>0.428</td>
<td>0.699471 +28</td>
<td>0.00850</td>
<td>668 +230</td>
</tr>
<tr>
<td>2.9&lt;d&lt;3.1</td>
<td>9.16</td>
<td>147.7</td>
<td>0.297</td>
<td>0.699544 +20</td>
<td>0.00581</td>
<td>675 +240</td>
</tr>
<tr>
<td>3.1&lt;d&lt;3.25</td>
<td>1.82</td>
<td>147.0</td>
<td>0.301</td>
<td>0.699450 +22</td>
<td>0.00532</td>
<td>790 +217</td>
</tr>
<tr>
<td>3.25&lt;d</td>
<td>1.85</td>
<td>126.5</td>
<td>0.532</td>
<td>0.699652 +32</td>
<td>0.01214</td>
<td>-</td>
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<tr>
<td>NBS 987</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.710237 +12</td>
<td>-</td>
<td>-</td>
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</table>
Fig. 4. The REE patterns of the samples from Y-82192. These are the separated samples by heavy liquids.
are lower than 3.25, the isotopic equilibrium can be considered to be almost established, because these fractions form a line (dotted line in Fig. 5) for a Rb-Sr system. This line gives an age of $698 \pm 98$ million years with the initial isotope ratio of $0.69939 \pm 6$ ($\lambda_{3-} = 1.42 \times 10^{-11}$/yrs). This age, $7 \times 10^8$ yrs, can be considered to indicate the age when this chip underwent an impact melting event. Figure 6, the plot of five samples (whole rock and separated samples with the densities lower than 3.25 g/cm$^3$), proves that the $7 \times 10^8$ yrs line in Fig. 5 cannot be a mixing line.

According to the $^{40}$Ar-$^{39}$Ar dating by Kaneoka and Takaoka (1987) of this chip (SubNo.63D), this sample has an age of about $4.1 \times 10^9$ yrs. This result appears too different to the age calculated in this study. However, this apparent discrepancy is interpreted to imply that the impact melting ($7 \times 10^8$ yrs ago) was not so intense and that the duration of molten state was too short to cause the degassing of radiogenic argon. For the very short-term vitrification, however, a partial (or local) homogenization of elements and isotopes took place, followed by the solidification or mineralization responsible for the redistribution of elements. Through this process, presumably a Rb-Sr systematics were at least partially reset for a limited size.
Fig. 6. The plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}(\text{ppm}^{-1})$.

Most lunar samples from the highlands on the moon have been known to show the ages around $3.9 \sim 4.0 \times 10^9$ yrs. The $^{40}\text{Ar}-^{39}\text{Ar}$ age (Kaneoka and Takaoka, 1987) for the glassy material is in keeping with these ages, suggesting that it originated from the highland area. Also, judging from the chemical characteristics of this sample (Y-82192), it is obvious that it came from the lunar highland.

Among lunar samples including mare samples, little sample with an age as young as $7 \times 10^8$ yrs has ever been known. Even for mare basalts, the common age is $2.7 \sim 3.4 \times 10^9$ yrs. Taken altogether, it would be reasonable to infer that the glassy material under consideration was formed at the event of formation of a young crater at a highland area. Thus far, ages of crater formations in highland have been estimated from the crater densities and the estimated cratering rate (Basaltic Volcanism on the Terrestrial planets, Chapter 8, 1981). According to Hartmann (1972), craters with ages around $7 \times 10^8$ yrs belong to young ones characterized by well-kept bright rays and rims (e.g., Copernicus, Kepler, Aristarchus, Tycho etc.). According to the estimation by some workers (Basaltic Volcanism on the Terrestrial planets, Chapter 8, 1981), the age of Copernicus is $0.8 \sim 1.5 \times 10^9$ yrs. And the K-Ar study of Apollo 12 samples gave the age of about $0.8 \times 10^9$ yrs as
the age of Copernicus formation (Alexander et al., 1976). However, since this crater exists in a mare district and there is little mare component in Y-82192, this crater should be excluded as a possible source. Other young rayed craters, such as Kepler or Aristarchus also exist in the maria. On the other hand, the age of the Tycho crater is $7^{+3}_{-6} \times 10^8$ yrs (Basaltic Volcanism on the Terrestrial planets, Chapter 8, 1981) and this crater exists in the highland. Therefore, it is probable that Y-82192 came from somewhere near Tycho. However, according to another estimation (Hartmann, 1972), the age of Tycho formation is around $1 \times 10^8$ yrs. But it should be noted that these estimations involve considerably large uncertainties. So it is difficult to identify definitely the origin of this meteorite by comparison of our radiometric age with those estimated roughly from cratering rate. For example, one cannot rule out a possibility that this meteorite might have been derived from the far side on the moon. This possibility is, however, low because the craters on the far side appear old. So far as the currently available data are concerned, it seems highly probable that the glassy sample studied by us came from the Tycho crater. Further studies of lunar glassy samples would throw clearer lights on the ages of crater formation and on the sources of glassy materials. Moreover, it is another problem to be studied whether the samples as examined here were ejected into the space at the time of crater formation (O'Keefe, 1959).

5. Summary

Since the formation of the solar system $4.5 \sim 4.6 \times 10^9$ yrs ago, many kinds of activities inducing melting events, have occurred on the planets and planetesimals. Most of the achondrites such as eucrite and diogenite can be considered to have been formed by the earliest differentiation event. As presented in section 2, this early igneous activity on the parent body for diogenites would have continued for around 100 million years. After those events, many collisions occurred and the melting events of various scales were induced. The study of lunar meteorites shows one example of such shock events. Shock metamorphism events are known not only for achondritic meteorites, but also for chondritic meteorites. Recently, some shock events, which occurred on L- or LL-chondrite parent bodies, have been precisely dated (Nakamura et al., 1990; Nakamura and Okano,
1985). These studies showed that some intense collisions took place on some of LL-chondrite parent bodies $1.2 \times 10^8$ yrs ago and on the L-chondrite parent bodies $4.6 \times 10^8$ yrs ago. These results indicate that collision events had occurred intermittently on the parent bodies of meteorites and that these collisions had taken a significant part in the metamorphism or igneous activities of the parent bodies.

The results mentioned above have been obtained using the $^{87}$Rb-$^{87}$Sr method. As a dating method, $^{40}$K-$^{40}$Ar, $^{147}$Sm-$^{143}$Nd, and U-Pb isotope systems are also commonly used. These methods can be applied chiefly to a silicate, oxide, or sulfide phase. Recently a $^{187}$Re-$^{186}$Os isotope system has been developed and used for the dating of iron meteorites. Luck et al. (1980) first examined this $^{187}$Re-$^{186}$Os isotope systematics on iron meteorites and metal phases in some meteorites, using the SIMS (Secondary Ion Mass Spectrometer). They improved the analytical method of the Re-Os system and reported the age of iron meteorites, $4.56 \pm 0.12 \times 10^9$ yrs (Luck and Allegre, 1983). Furthermore, some new analytical techniques using the ICP ion source or resonance ionization has been developed (ICP-MS, RIMS or LAMMA). Several scientists (e.g., Hirata et al., 1988; Lindner et al., 1989) have made practicable and refined this isotopic system using the new analytical method mentioned above. This isotopic system shall be used as a potent dating method for iron meteorites, stony-iron meteorites, or metal phases in other meteorites. By the precise use of these various isotopic systems, we will be able to get detailed information of the time scale in the evolution of the solar system.

Acknowledgements

This work was supported by the Grant-in-Aid for Scientific Research on Priority Areas (Origin of the Solar System) of Japanese Ministry of Education, Science, and Culture (Nos. 62611003, 63611003, and 01611003).

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