Rubidium-87/Strontium-87 Age of Juvinas Basaltic Achondrite and Early Igneous Activity in the Solar System

Abstract. *A (4.60 ± 0.07) × 10^9 year internal isochron has been drawn for the achondrite Juvinas by the rubidium-87/strontium-87 method. Earlier petrographic investigation of achondrites supplemented by a new ion microprobe study of Juvinas strongly suggest an igneous origin for this class of meteorites. The results thus indicate that igneous activity may have rapidly followed the formation of the achondrites' parent body 4.6 × 10^9 years ago.*

The eucrites or "basaltic achondrites" constitute a class of meteorites for which an igneous origin is almost unequivocally documented [for example, see Duke and Silver (*1*)]. The eucrites form such a chemically homogeneous population of meteorites (*2*) that we may reasonably assume that they originated from a single planetary body (hereafter denoted BAP, basaltic achondrite parent body) which has now disappeared. These basalts, which, in general, are brecciated, show great similarities in texture, chemistry, and rare gas contents with lunar basalts. Oxygen isotope data for lunar rocks and the eucrites (*3*) are so different, however, that a possible lunar origin for the latter is practically excluded.

One major result of the recent moon exploration program has been correlated information on the petrological, chemical, and chronological evolution of lunar rocks. Together with our ever-increasing knowledge of our own planet, this is an important step forward in our understanding of the evolution of the solar system. The study of eucrites with the techniques developed for lunar rocks may ultimately allow a comparison of the BAP evolution with that of other planets.

The ages of several eucrites, determined by the conventional ^{40}K-^{40}Ar method (*4*), vary between 2.2 and 4.4 × 10^9 years. Because of argon loss, these most likely represent cooling ages. More recently, the ^{39}Ar-^{40}Ar technique has been applied to four eucrites (*5*). The argon release patterns were quite complex, however, and no clear determination earlier than 4.4 × 10^9 years was found. Uranium-thorium-lead data have been obtained for some eucrites (*6*). Recomputation of the data gave some concordant ages at 4.6 × 10^9 years (4.55 × 10^9 years based on the use of a newly determined ^{235}U decay constant) whereas some others were discordant. Several eucrites were used to draw a total rock isochron by the ^{87}Rb-^{87}Sr method (*7*). An age of (4.39 ± 0.26) × 10^9 years was obtained, the relatively large uncertainty being due to the small range of the observed $^{87}Sr/^{86}Sr$ ratio.

All ages obtained so far on eucrites were from total rock samples. To be sure, total rock determinations are an important step in unraveling the evolution of the meteorites, but, as Papanastassiou and Wasserburg (*8*) showed for the lunar rocks, a determination of the internal isochron (*9*) is mandatory if one is to obtain information on crystallization history. The aim of this study was to determine an internal isochron for the achondrite Juvinas so as to obtain a lower limit for the time of magmatism responsible for its formation.

Precise internal isochrons can only be obtained for samples giving a relatively large spread of rubidium and strontium concentrations in the separated phases. Such is not often the case for rocks of basaltic composition. Many lunar basalts do, however, contain fine interstitial phases rich in potassium and rubidium, thus providing the desirable spread (*10*). The imaging ion microprobe can be used with advantage to detect such minute compositional heterogeneity. We studied polished sections of samples of the Juvinas meteorite with a Cameca SMI 300 analyzer. This instrument allows direct imaging of secondary ion emission for any ionic species in an area 300 μm in diameter. In addition to showing that potassium-rich and rubidium-rich phases, not unlike those in lunar rocks, were indeed present, the study gave additional textural and compositional details of the other phases present. A representative set of selected ion distribution photographs is given in Fig. 1. The sample area shows the most important minerals encountered. A portion of the grains richest in silicon are also rich in potassium and presumably represent the tridymite polymorph, whereas the other grains are quartz. Relatively large areas rich in silicon, calcium, aluminum, sodium, and potassium are thought to be unrecrystallized glass. The area to the right in the pictures is occupied for the most part by a pyroxene grain showing fine exsolution lamellae (approximately 1 μm wide). Interstitial lathlike plagioclase and a fine-grained potassium-rich phase are also present. Other features, such as plagioclase and pyroxene zoning and brecciation described elsewhere (*1, 11*), were commonly observed. The textures and compositional variations of the phases clearly stem from an igneous origin, whereas the finely separated pyroxenes indicate that relatively rapid cooling occurred. Brecciation apparently was not strong enough to destroy the primary textures.

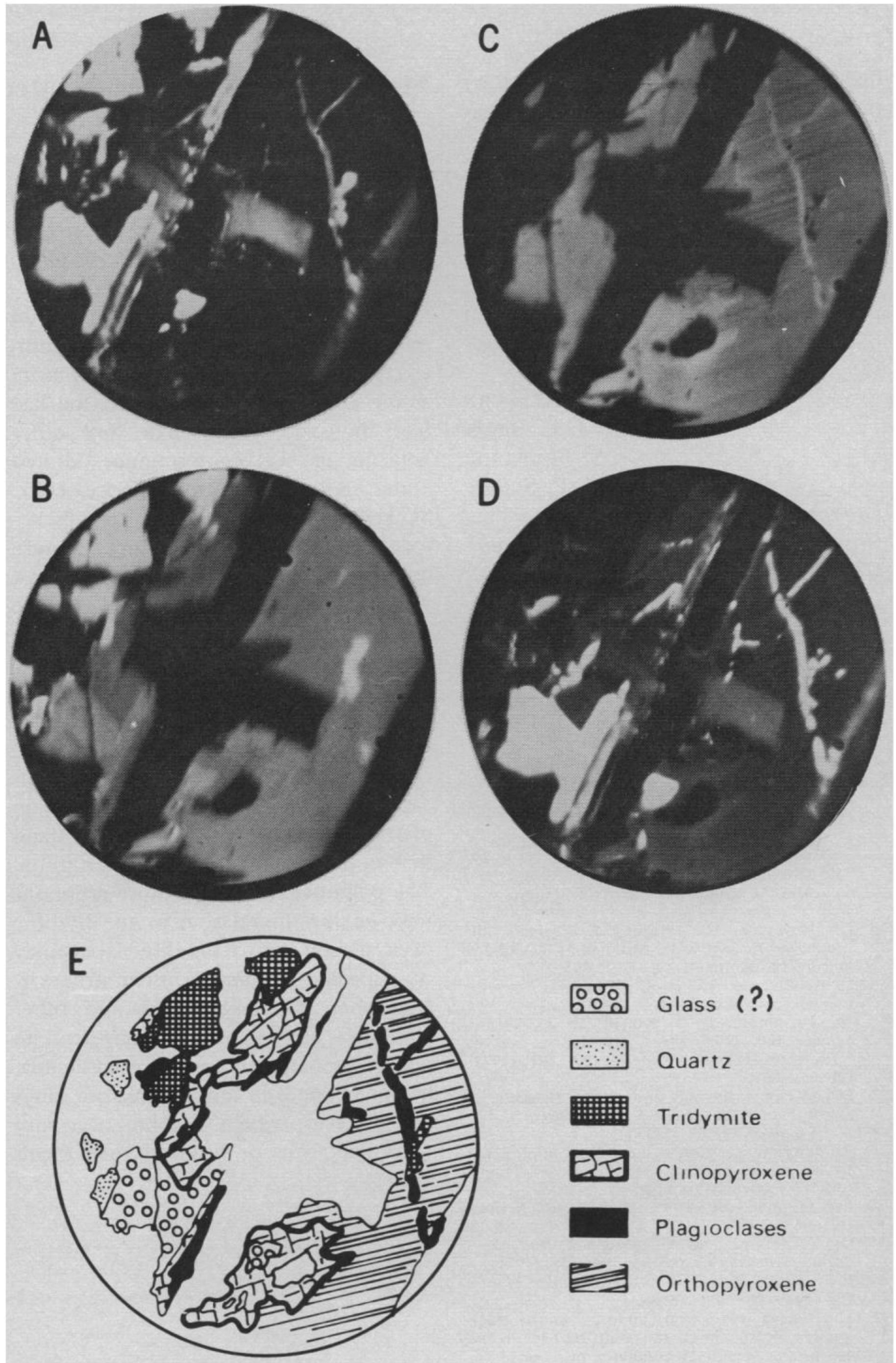
Knowing that potassium-rich microphases were present, we were especially careful in our mineral separation procedure. Mineral separates were obtained with heavy liquids and treated by our usual chemical preparation technique (*12*). A programmable magnetic field mass spectrometer was used to determine the isotopic compositions of rubidium and strontium, and concentrations were determined by isotopic dilution. Total blanks amounted to 0.03 × 10^{-9}, 0.11 × 10^{-9}, and 35 ×

Table 1. Rubidium-strontium isotopic composition and potassium, rubidium, and strontium concentration for Juvinas; ppm, parts per million.

Sample	$^{87}Rb/^{86}Sr$*	$^{87}Sr/^{86}Sr$*	K (ppm)	Rb (ppm)	Sr (ppm)	Weight (mg)	ξ†
Glass (?)	0.0876 (6)	0.70473 (8)	900	1.356	44.82	3	− 0.48
Tridymite + quartz	0.0231 (2)	0.70063 (5)	956	0.738	92.55	5	+ 1.8
Plagioclase	0.00301 (2)	0.69914 (4)	560	0.1773	17.05	17.4	− 0.55
Pyroxene	0.00714 (5)	0.69950 (15)	83	0.0480	19.48	15	+ 0.75
Total rock	0.00407 (5)	0.69927 (3)	248	0.1114	79.1	36.4	+ 0.30

* Numbers in parentheses are the standard deviations of the last decimal place ($\pm 2\sigma/\sqrt{N}$). † $\xi = \frac{(^{87}Sr/^{86}Sr_{\text{measured}} - ^{87}Sr/^{86}Sr_{\text{calculated}})}{^{87}Sr/^{86}Sr_{\text{measured}}} \times 10^4$.

Fig. 1. Ion microprobe photographs and interpretative sketch for a sample of Juvinas. The area shown is approximately 300 μm in diameter. (A) $^{39}K^+$; (B) $^{28}Si^+$; (C) $^{40}Ca^+$; (D) $^{23}Na^+$; (E) interpretative sketch. Areas left in white on the sketch represent an evaporated gold grid or plucked-out material.



10^{-9} g per gram of sample, for rubidium, strontium, and potassium, respectively. During the course of the work, National Bureau of Standards standard SRM 987 was repetitively tested and gave an average value for $^{87}Sr/^{86}Sr$ of 0.71017 with a standard deviation of 0.00002 ($\pm 2\sigma/\sqrt{N}$, where N is the number of samples).

Experimental results are given in Table 1 and plotted on a conventional $^{87}Sr/^{86}Sr$, $^{87}Rb/^{86}Sr$ diagram (Fig. 2). Linear regression analysis of the experimental points yielded a slope corresponding to an age of $(4.60 \pm 0.07) \times 10^9$ years, based on use of the ^{87}Rb decay constant of 1.39×10^{-11} year^{-1} (*13*). This age is close to those obtained for some chondrites and iron meteorites by the ^{87}Rb-^{87}Sr internal isochron method (*14*). The initial $^{87}Sr/^{86}Sr$ ratio for Juvinas obtained from our experimental data is 0.69898 ± 0.00005. Considering a maximum interlaboratory systematic bias of 0.0001, this initial ratio is identical to that found by the group at the California Institute of Technology (*7*) for the total rock isochron of eucrites.

The results provide crucial information on the BAP evolution:

1) The $(4.60 \pm 0.07) \times 10^9$ year age is the age of the last rubidium-strontium equilibration. It may represent the age of basalt formation on the BAP or the brecciation episode subsequent to it. In any case, volcanism responsible for Juvinas formation is not any younger.

2) Since the initial $^{87}Sr/^{86}Sr$ ratio for the total rock eucrites and Juvinas are identical within experimental errors, the processes that gave rise to rubidium-strontium fractionation and basalt formation must have been almost contemporaneous. It is thus very likely that the eucrites are samples of a body which differentiated magmatically in the early history of the solar system. A corollary of this observation is that, even if the BAP resulted from heterogeneous accretion, this would have been obscured by pervasive melting and rehomogenization.

3) The source of energy for an early melting process remains unset-

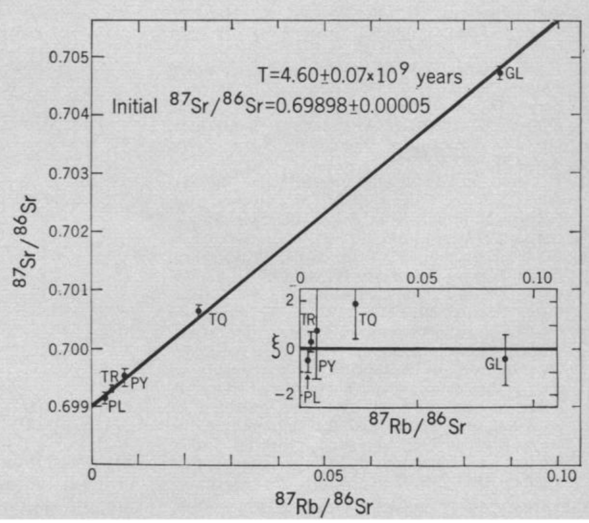


Fig. 2. Rubidium-strontium isotopic evolution diagram for Juvinas; *PL*, *TR*, *PY*, *TQ*, and *GL* correspond to the plagioclase, total rock, pyroxene, tridymite + quartz, and glass samples, respectively. The inset shows the deviation (ξ) of each sample from the regression line as a function of $^{87}Rb/^{86}Sr$ (*7*).

tled. Gravitational energy released by the accretion process, a possible mechanism, requires that the BAP was at least of lunar size. Urey has commented on the existence of such bodies in the early solar system (*15*). The short-lived ^{26}Al radioisotope is another possible heat source. Its detection in primitive objects of the solar system is the subject of renewed interest (*16*).

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10. For example, see A. L. Albee *et al.*, *Science* **167**, 463 (1970).
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13. The linear regression analysis is a least-squares fit to the data point based on the use of the Wendt II computer program especially designed for rubidium-strontium age determinations [C. Brooks, S R. Hart, I. Wendt, *Rev Geophys Space Phys.* **10**, 551 (1972)].
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17. Our interest in meteorites is the result of the enthusiastic encouragement of Dr. P. Pellas in this country. We are indebted to G. Unal and M. Girard for maintaining the mass spectrometer in good working order. Institut de Physique du Globe contribution number IPG NS 135.

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Mount St. Helens Volcano: Recent and Future Behavior

Abstract. *Mount St. Helens volcano in southern Washington has erupted many times during the last 4000 years, usually after brief dormant periods. This behavior pattern suggests that the volcano, last active in 1857, will erupt again—perhaps within the next few decades. Potential volcanic hazards of several kinds should be considered in planning for land use near the volcano.*

Mount St. Helens, a prominent but relatively little known volcano in southern Washington (Fig. 1), has been more active and more violent during the last few thousand years than any other volcano in the conterminous United States. Although dormant since 1857, St. Helens will erupt again, perhaps before the end of this century. Future eruptions like those of the recent past would affect a broad area beyond the volcano, but the area most likely to be severely affected is not yet heavily populated.

The high probability, based on past behavior, that Mount St. Helens will erupt again indicates that potential volcanic hazards should be considered in planning for future uses of the land that could be affected by an eruption. The potential risk from future eruptions may be low in relation to the lifetime of a person or to the life expectancy of a specific building or other structure. But when dwelling places and other land uses are established, they tend to persist for centuries or even millennia. Major changes in long-established land-use patterns, which become necessary to protect lives or property, can themselves be economically disastrous and socially disruptive; therefore, potential volcanic hazards should be considered while choices can still be made with respect to future land use, even though eruptions may still be decades away.

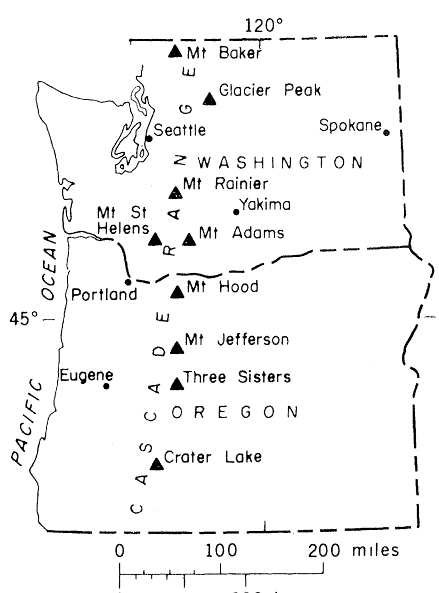

Fig. 1. Index map of Washington and Oregon showing location of Mount St. Helens and other volcanoes.

Because of its smooth, little-eroded slopes, Mount St. Helens has long been known to be younger than the neighboring volcanoes such as Mounts Rainier, Adams, and Hood (*1*). However, we have learned only recently how young St. Helens is and how often it has erupted in the recent past. Although its history extends back more than 37,000 years (*2, 3*), virtually the entire visible volcano has formed since about 500 B.C., and most of its upper part has been built within the last few hundred years (Fig. 2) (*4*). This knowledge of its formation resulted largely from detailed studies of the origin and sequence of the volcano's eruptive products, coupled with nearly 30 radiocarbon dates from which the volcanic chronology is inferred. The numerous dates were made possible by abundant charcoal in the deposits of many pyroclastic flows (avalanches of hot, dry rock debris) and by charcoal and other vegetative matter interbedded with tephra (explosively erupted, airborne debris).

Our purpose in this report is to summarize a remarkable and generally unrecognized record of recent activity at Mount St. Helens and to compare it with the history of some other well-known volcanoes. We also assess the significance of the present dormant interval, which has lasted nearly 120 years. The data now available suggest that since about 2500 B.C. the volcano has never been dormant for more than about five centuries at a time and that dormant periods of one or two centuries, or less, have been more typical.

Even apparently dormant intervals may have been broken by eruptions that did not leave a conspicuous deposit. The eruptions noted in our chronology include only those which produced deposits large enough to be preserved and recognized today. As many or more eruptions may have oc-