Articles

Flood Basalt Volcanism During the Past 250 Million Years

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A chronology of the initiation dates of major continental flood basalt volcanism is established from published potassium-argon (K-Ar) and argon-argon (Ar-Ar) ages of basaltic rocks and related basic intrusions. The dating is therefore independent of the biostratigraphic and paleomagnetic time scales. Estimated errors of the initiation dates of the volcanic episodes determined from the distributions of the radiometric ages are, approximately, plus or minus 4 percent. There were 11 distinct episodes during the past 250 million years. Sometimes appearing in pairs, the episodes have occurred quasi-periodically with a mean cycle time of 32 ± 1 (estimated error of the mean) million years. The initiation dates of the episodes are close to the estimated dates of mass extinctions of marine organisms. Showers of impacting comets may be the cause.

Flood basalts (or plateau basalts) are large accumulations of basaltic lavas characterized by great thickness and low surface relief. Flood basalt provinces occupy areas of 0.2×10^6 to 2×10^6 km^2, and thicknesses in places can exceed 1 km (*1–3*). Episodes of flood basalt volcanism are believed to consist of a series of large eruptions that create separate but overlapping lava flows, which give many exposures a terrace-like appearance commonly known as "traps" (from the Swedish word for "stairs"). Mafic intrusions are commonly associated with the extruded basalts, as are less abundant interbedded silicic volcanic rocks.

Flood basalt episodes are thought to mark the initiation of a subcontinental hot spot, and most such episodes were followed by rifting and continental fragmentation (*4*). Many flood basalts are therefore located near present continental margins. Some flood basalts along present continental edges were contiguous before continental separation (for example, the Serra Geral basalts of South America and the Namibian basalts of South-West Africa). Few flood basalts older than about 250 million years ago (Ma) are known; most of the older flows were probably destroyed when the ocean basins created by rifting eventually closed as a result of plate subduction accompanied by continental collision. Thus, flood basalts are well preserved only for the last cycle of continental rifting, roughly the last 200 million years. A few flood basalts older than 250 Ma, for example, the Permo-Triassic Siberian basalts and the Proterozoic Keweenawan basalts, may represent zones of incipient rifting without later continental separation. Other early episodes of flood basalt volcanism are represented today only by extensive swarms of feeder dikes, the basalt flows having been entirely removed by erosion (*1*).

In this article, we analyze statistically a large collection of published radiometric ages of the 11 known continental flood basalts of the last 250 million years. Only basaltic lavas and some related basic intrusive rocks are considered to be representative of the major episodes. A statistical method is employed for estimating the initiation dates of these episodes, which appear to have been relatively short-lived events during their major phases (lasting less than 3 million years). Within estimated dating errors, the timing of the outbreaks correlates well with the occurrence of mass extinctions of marine organisms. Furthermore, a quasi-periodicity may be present in the data.

Age Determinations

Most flood basalts have been dated by the use of the ^{40}K-^{40}Ar method on whole-rock samples or mineral separates. However, K-Ar ages are subject to a number of uncertainties arising from loss of radiogenic ^{40}Ar due to slow leakage from poorly retentive, weathered, or hydrothermally altered minerals (*5*) or to complete loss during contact metamorphism around later intrusions (*6*). Furthermore, any excess radiogenic argon incorporated into igneous rocks when the magmas crystallized (from xenoliths, for example) could result in apparent K-Ar ages that are older than the actual time of crystallization.

Techniques have been developed to help identify partially reset or anomalously old K-Ar ages (*6*). The ^{40}Ar-^{39}Ar method relies on the conversion of a measured portion of the natural isotope ^{39}K in a rock sample to ^{39}Ar by neutron irradiation in a reactor. If certain constants are known, ^{40}K/^{40}Ar can then be estimated from the argon-isotope ratio. One advantage to the ^{40}Ar-^{39}Ar method is that the sample can be incrementally heated and degassed, leading to an age spectrum that ideally rises to a plateau with increasing release of ^{39}Ar. If no plateau is reached, the age of crystallization may be roughly approximated by the use of a best-fit isochron on a plot of ^{40}Ar/^{36}Ar against ^{39}Ar/^{36}Ar for a suite of co-magmatic samples. In a few cases, a third method has been used in which isochrons are read from a plot of ^{40}Ar/^{36}Ar against ^{40}K/^{36}Ar.

We have not attempted to correct the early published K-Ar ages for subsequent revisions of the radioactive decay constants because the resulting errors in the ages for the time period of interest are at most about 2%. Estimated accidental errors are twice as large as this known systematic error. In cases where a straight average age of several replicate analyses was reported, we have used only this average age; otherwise, we included replicate ages as separate entries in our compilation (except for Antarctica where a large number of replicate ages were obtained on a small number of samples).

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Rubidium-strontium (Rb-Sr) ages were considered only as secondary methods of dating because of their commonly large associated errors (*6*).

Distributions of the Apparent Ages

Because conventional K-Ar ages are the most abundant ages available for flood basalts, and because even the better determined argon-isotope ages can show dispersions of up to ±20%, we grouped together all the K-Ar and Ar-Ar ages into a single histogram for each flood basalt province. The distributions of ages for the various provinces typically have an asymmetric appearance, showing a few older ages, a relatively sharp increase in the number of younger ages climbing to a maximum, and an erratically decreasing tail of still younger ages (Fig. 1). Recent work on individual flood basalt episodes has shown that the long tail of young ages in many cases is the result of argon losses from altered samples, whereas the oldest ages may have been affected by initial incorporation of some excess argon. The total apparent age spread can reach tens of millions of years in some cases.

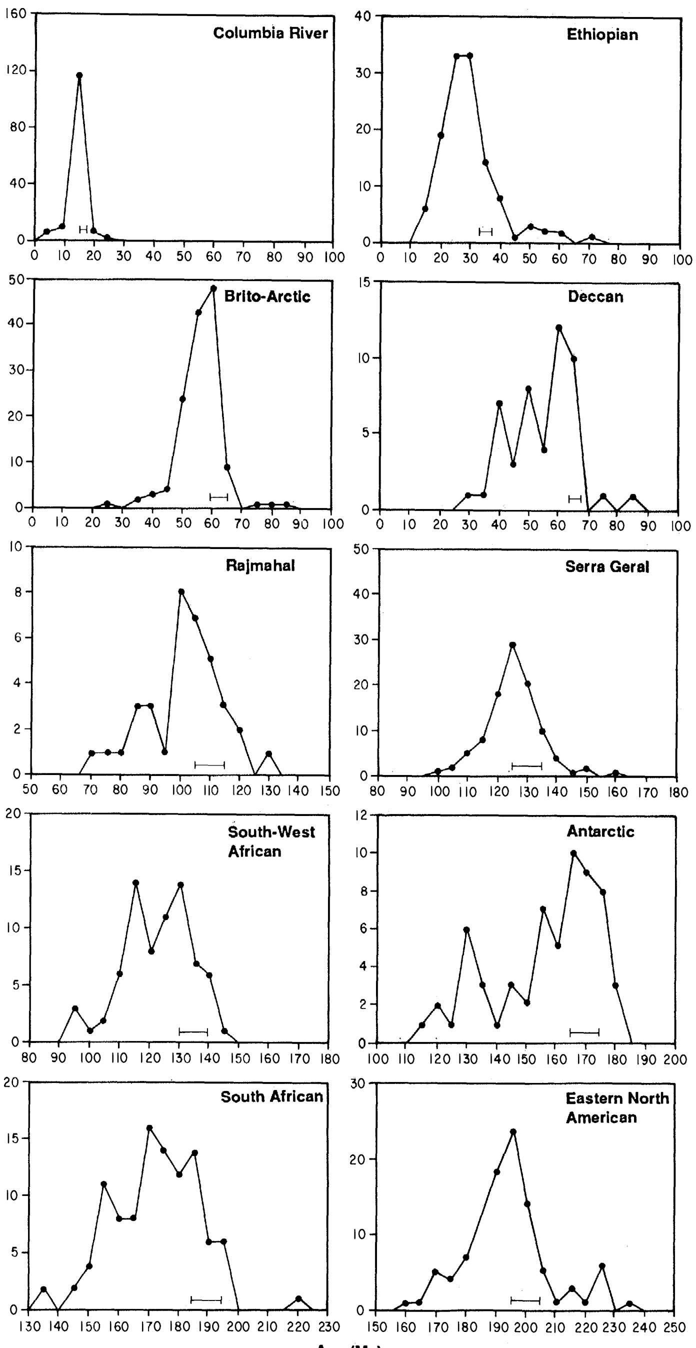

Fig. 1. Histograms of K-Ar and Ar-Ar ages for the ten known post-Paleozoic continental flood basalt episodes. A bar indicates the probable range of accidental and systematic errors for the initiation date of the episode.

The most accurate radiometric ages, however, suggest that eruption of most of the lava in any episode occurred over times of less than a few million years and possibly less than 1 million years. In several cases, paleomagnetic evidence is available and supports this conclusion. Furthermore, observed flow boundaries in flood basalt provinces typically display little or no erosional relief and only thin interflow deposits. However, minor, intermittent activity probably persisted for some time after the main eruptions and may account for a number of the younger ages in the distributions.

How can the true start dates of the episodes be estimated from distributions of ages with such wide variances? Because of the uneven nature of the distributions, the modes are not well defined, even after we smoothed the distributions with a filter that computes repeated running means of the data points. The mode, in any case, probably does not represent the true start date of the main phase of an episode. We have more reasonably identified the age at which the distribution shows its steepest slope in its rapid rise to a maximum in age histograms, where the bin size used is 5 million years. For four provinces that have published argon-isotope plateau ages, we used age spectra showing proper, well-defined plateaus to provide a partly independent method of dating. This procedure allows us to make a comparison of all the flood basalt age distributions within the same framework and with the same assessment criteria, and provides generally good agreement with the ages that most recent investigators have associated with the major phase of each episode. Error estimates that we have attached to the assigned ages cover the full ranges of likely accidental and systematic errors.

Flood Basalt Episodes

Columbia River Basalt Group. The Columbia River basalts of the northwestern United States today cover an area of 200,000 km^2 (*7*). They are atypical of flood basalts as they do not mark a zone of continental separation (at least not at present), but appear to have been erupted in a back-arc extensional setting (*1*). Possibly they are related to the Yellowstone hot spot, which would have been located beneath the Columbia River Plateau region about 15 Ma.

We have collected 116 published whole-rock K-Ar ages and 14 Ar-Ar ages for the Columbia River basalts proper and 13 additional K-Ar ages for related basalts in coastal Oregon and Washington (*8, 9*). The plotted age distribution (Fig. 1) indicates a start date of 17 ± 1 Ma. Use of a smaller bin size or of only the best Ar-Ar ages gives the same result. This also agrees with paleomagnetic evidence that the bulk of the eruptions occurred in a 2-million-year interval at some time between magnetic chrons 6 and 5 (*8*).

Ethiopian basalts. The Ethiopian basalts of the voluminous Older Trap Series include the Blue Nile, Ashangte, and Aiba basalts in northern Ethiopia, the Geba basalts in western Ethiopia, and the Lower Stratoid basalts in southeastern Ethiopia. Together with related rocks in northern Kenya and southern Yemen, the basalts crop out over a total area (before the opening of the Red Sea and Gulf of Aden) of 750,000 km^2 (*10–13*).

Behre and co-workers (*10*) have compiled a list of 74 K-Ar ages older than 24 Ma (based mostly on whole-rock analyses) for Ethiopian basaltic rocks; the list contains both published and previously unpublished ages. Grasty and co-workers (*13*) reported another 7 K-Ar ages. Abbate and Sagri (*14*) listed 16 K-Ar ages for Older Trap units which fall between 18 and 24 Ma, and Megrue and co-workers (*15*) reported 25 K-Ar ages for possibly related dikes that fall in the range 15 to 24 Ma. Still younger rift-related volcanic units also occur, but these are not regarded as flood basalts because of their small volumes (*10, 11*), and therefore we have not included them. Based on 122 ages, the start date of the main phase of the eruption (Fig. 1) is 35 ± 2 Ma.

Brito-Arctic basalts. Lower Tertiary flood basalts occur across northwestern Britain, northern Ireland, and the Faeroe Islands. Equivalent rocks occur in East Greenland, and rocks that are possibly equivalent occur in West Greenland and on Baffin Island. Together these rocks form the Brito-Arctic Basalt Province (*16*). The total area covered is about 100,000 km^2, but it was probably much greater before continental rifting and subsequent erosion. Seismic reflection studies on the submerged margins of the northeastern Atlantic coastlines reveal massive sequences of basalt flows and sills, occupying a total volume of 1×10^6 to 2×10^6 km^3 and apparently correlated with the Brito-Arctic basalts exposed on land (*17*).

Evans and co-workers (*18*) reviewed published K-Ar ages of British Tertiary igneous rocks and reported 37 additional ages, consisting of conventional K-Ar ages as well as a few Ar-Ar ages. From their data we derive a total of 65 ages for basaltic lavas and related basic dikes (*18*, tables 1, 2, and 3); 70 additional ages come from other sources (*19, 20*). Nearly all these ages span the range 65 to 50 Ma. Eight Ar-Ar ages with well-defined age plateaus show a range from 62 to 55 Ma. A single K-Ar age of 58 ± 2 Ma is available for lava flows on Baffin Island, and two closely similar ages, 54 ± 1.5 and 55 ± 1.5 Ma, characterize a gabbroic intrusion in West Greenland (*21, 22*). Beckinsale and co-workers (*22*) reported a Rb-Sr isochron age of 65 ± 5 Ma for the West Greenland basalts. Putting all 138 K-Ar and Ar-Ar ages together, we estimate (Fig. 1) that the Brito-Arctic flood basalts began erupting at 62 ± 3 Ma, at about the time of the initial rifting of the Norwegian Sea (*23*).

Paleomagnetic data, coupled with the near absence of interflow layers, suggest that the major eruptive phase was relatively short-lived, lasting less than 3 million years. The bulk of the British Tertiary basalts probably were erupted during the single reversed magnetic chron 26R (*19*), which ranges from 63 to 59 Ma (*24, 25*), whereas the eruption of the East Greenland basalts may have occurred slightly later, between magnetic anomalies 25 and 24 (*23*), or 58 to 53 Ma (*24, 25*).

Deccan Traps. The Deccan Traps of India cover an area of about 500,000 km^2, but were probably originally much more extensive (*3, 26, 27*). Although the presence of numerous interflow sedimentary beds and soil horizons indicates that activity was occasionally interrupted, the surfaces of the Deccan flows are flat and there is little evidence for erosion between the lava flows. The magma apparently emerged quickly; quiet periods may have lasted at most several 10^4 years between major eruptions (*28*).

Courtillot and co-workers (*26*) have compiled 34 published K-Ar ages (including four Ar-Ar age spectrum determinations) and have added 14 ages from their own work. According to Fig. 1, which has been plotted from their compilation, the start date of the eruptions is 66 ± 2 Ma. Two reliable Ar-Ar plateau ages from Kaneoka (*29*) are 68 and 63 Ma. Paleomagnetic evidence is consistent with a date of 67 to 65 Ma if the reversed magnetic chron during which most of the lava emerged is 29R; this is the same chron as that in which the Cretaceous-Tertiary boundary lies (*24–26, 30*).

Rajmahal Traps. The Rajmahal basalts of eastern India are exposed today over an area of more than 4000 km^2, and they also occur in the subsurface beneath the Bengal Basin. All of these basaltic rocks were most likely contiguous with the Bengal and Sylhet traps, and therefore may have originally covered an area of at least 200,000 km^2 (*31*). Stratigraphic evidence suggests that the Rajmahal basalts were erupted before the Late Cretaceous, most likely during the Late Jurassic or Early Cretaceous. Paleomagnetic measurements suggest that the bulk of the lava was erupted within one normal polarity chron (*32*).

Table 1. Ages of flood basalt initiations and mass extinctions.

Flood basalts: Episode	Age* (10^6 years)	Mass extinctions: Stage (*59*)	Age† (10^6 years)
Columbia River (U.S.)	17 ± 1	Lower to middle Miocene‡	14 ± 3
Ethiopian	35 ± 2	Upper Eocene	36 ± 2
Brito-Arctic	62 ± 3	Maastrichtian	65 ± 1
Deccan (India)	66 ± 2		
		Cenomanian	91 ± 0
Rajmahal (India)	110 ± 5	Aptian§	110 ± 3
Serra Geral (S. America)	130 ± 5	Tithonian	137 ± 7
South-West African	135 ± 5		
Antarctic	170 ± 5	Bajocian‖	173 ± 3
South African	190 ± 5	Pliensbachian	191 ± 3
Eastern North American	200 ± 5	Rhaetian/Norian	211 ± 8
Siberian	250 ± 10	Dzulfian/Guadalupian	249 ± 4

*Uncertainty estimate covers the probable range of accidental and systematic errors. †Average age of the upper stage boundary, according to three time scales (*25, 60*), whose range of differences is indicated. ‡Incorporating other fossil evidence (*61*). §Possible mass extinction at the genus level (*59*). ‖Regarded as a significant mass extinction (*62, 63*).

McDougall and McElhinny (*32*) made 16 K-Ar age determinations on both whole rocks and mineral separates from flows in the West Bengal and Bihar areas; Murthy (*33*) reported another 4 K-Ar ages obtained originally by the Geological Survey of India; Agrawal and Rama (*34*) added 8 more K-Ar ages; and Baksi and co-workers (*31*) derived 8 Ar-Ar ages. The start date is probably 110 ± 5 Ma (Fig. 1); the comparatively large uncertainty is due to the small number of ages as well as to the discrepancies among the ages derived with different methods. Baksi and co-workers (*31*) preferred a start date of about 115 Ma.

Serra Geral (Paraná) basalts. The Serra Geral (or Paraná) basalts cover an area of 1.2×10^6 km^2 (probably originally about 2×10^6 km^2) in Brazil and in parts of Paraguay, Uruguay, and northern Argentina. Paleomagnetic measurements on these basalts suggest that most of the magma was extruded in less than a few million years (*35*).

A total of 101 K-Ar ages, mostly on whole-rock analyses of lavas and of coeval intrusives (*36, 37*), indicate a start date of 130 ± 5 Ma (Fig. 1). A Rb-Sr isochron age for a small sample of Uruguayan basalts is 120 ± 5 Ma (*38*). These age determinations support the view that the Serra Geral basalts occurred just before the initial opening of the South Atlantic Ocean (*35*) and were approximately coincident with similar eruptions in southwestern Africa as described below.

South-West African (Namibian) basalts. Several areas of basalt flows and related intrusions in southwestern Africa (Namibia) have been considered part of the Karroo series of South Africa: (i) the Kaoko basalts, making up the Etendeka Plateau in Namibia, (ii) the Hoachana basalts to the southeast, and (iii) the Keetsmanshoop intrusions even farther to the south. If originally contiguous, these basaltic rocks may have covered an area of about 500,000 km^2. The three separate geographic provinces contain rocks in at least two distinct age groups; the more southerly Keetsmanshoop intrusions are the oldest (*39*) and evidently belong to an earlier period of volcanism.

A total of 73 K-Ar ages for the younger basalt flows in southwestern Africa (*37, 39, 40*) yield a start date of 135 ± 5 Ma (Fig. 1). In addition, four minor episodes of alkaline volcanism have occurred since that time (*41*).

Antarctic basalts. On the Antarctic continent, the Ferrar dolerite sills and the Kirkpatrick basalt flows make up the Ferrar Group, which crops out in a linear belt extending 4000 km along the central Transantarctic Mountains (*42*). Although these basalts are widespread, they may not represent a true flood basalt episode.

We have compiled 61 published K-Ar and Ar-Ar ages for both whole rocks and mineral separates (*42–46*). These ages yield a start date of 170 ± 5 Ma (Fig. 1). Fleck and co-workers (*45*) have published one reliable Ar-Ar plateau age, which is 170 Ma. Many of the apparently young rock samples seem to have suffered extensive Ar loss (*42–46*), which is probably the reason for the wide scatter and double peak in the overall age distribution. Moreover, some of the uppermost basalt flows yield the oldest ages. Compston and co-workers (*43*) obtained a Rb-Sr isochron age of 151 ± 18 Ma from 18 samples of the Ferrar dolerite.

Dolerites in Tasmania that are similar to the Antarctic rocks are found exposed over an area of 15,000 km^2. McDougall (*47*) has published 11 K-Ar age determinations on sampled mineral separates, which yield an average eruption date (from a single intrusion) of 165 ± 5 Ma. Schmidt and McDougall (*48*) give for several intrusions an average eruption date of 174 ± 8 Ma. These dates suggest that the Tasmanian dolerites were essentially contemporaneous with the basaltic rocks of Antarctica.

South African basalts. The Karroo System of igneous rocks and coeval sedimentary rocks crops out widely over a large area of southern and southeastern Africa, and originally covered more than 1.5×10^6 km^2. The series includes the Stormberg and Drakensberg basalts in South Africa (mostly within Lesotho), the Lebombo basalts in Swaziland and along the border between South Africa and Mozambique, the Nuanetsi and related basalts along the border between South Africa and Zimbabwe, and some outliers farther north (*49*). The rocks are preserved in troughs and down-faulted basins; the faulting seems to have been contemporaneous with much of the igneous activity. The whole episode was most likely related to rifting along what is now the east coast of South Africa (*49*).

We have compiled 116 K-Ar ages from published whole-rock and mineral-separate measurements made both on Karroo basalts (*44, 49, 50*) and on basalts from the southern regions of Namibia (*37, 39, 40*). The probable start date (Fig. 1) is 190 ± 5 Ma. Rb-Sr ages, determined from several Zimbabwean, Lebombo, and Nuanetsi alkalic and silicic volcanic rocks are 197 ± 15, 191 ± 13, and 194 ± 12 Ma, respectively (*49*).

Eastern North American basalts. The Upper Triassic to Lower Jurassic basalts of eastern North America are related to the initiation of rifting between North America and Africa (*1*). Although the exposed lava flows and intrusions are today restricted to down-faulted Mesozoic basins stretching from Nova Scotia to North Carolina, "feeder" dikes are much more widespread (*51*). The Eastern North American Basalt Province has been classified as a small example of continental flood basalt volcanism (*1*), but extensive basalt layers have recently been detected in the subsurface of eastern North America and the adjacent continental shelf; these layers cover an area of more than 100,000 km^2 (*52*). The eastern North American basalts clearly have the dimensions of a true flood basalt province.

We have collected 104 published K-Ar and Ar-Ar ages (based on various methods) for basaltic flows, dikes, and sills in scattered localities from Nova Scotia to North Carolina (*53*). From the age distribution (Fig. 1), we estimate a start date of 200 ± 5 Ma. Four Ar-Ar ages based on well-defined age plateaus, in the Newark and Hartford basins, range from 193 to 187 Ma, and five good Ar-Ar ages from rocks in Virginia range from 201 to 193 Ma.

Siberian basalts. The flood basalts of the Siberian Platform cover an area of more than 1.5×10^6 km^2. Eruption of these basalts was possibly related to the present Jan Mayen hot spot. DePaolo and Wasserburg (*54*), in surveying the Russian literature, report that whole-rock K-Ar ages for the Siberian basalts peak between 250 and 240 Ma. The literature survey by Holser and Magaritz (*55*) likewise indicates a mean K-Ar age of 250 ± 9 Ma. This agrees with the 4 K-Ar ages published by Dmitriyev and Guseva (*56*), which cluster closely around 250 Ma. We estimate the start date as 250 ± 10 Ma.

Flood Basalts and Mass Extinctions

Initiation dates of the 11 continental flood basalt episodes just discussed are listed in Table 1. Because a possible connection has been suggested between flood basalts and mass extinctions (*57, 58*), we have also presented estimated dates of the ten major extinctions of marine life during the past 250 million years. The list of mass extinctions comes from a tabulation by Raup and Sepkoski (*59*), who provided separate dates for each episode according to three geological time scales (*25, 60*). In each case, we have simply adopted a straight average of the three geological dates, whose full range is also given in Table 1. In two cases, the lower to middle Miocene and Bajocian extinction events, we have incorporated additional paleontological information (*61–63*).

Recognizing that the Brito-Arctic and Deccan eruptions started at about the same time, as probably did the Serra Geral and South-West African eruptions, we find a close correspondence between episodes of flood basalt volcanism and episodes of mass extinctions. The one possible exception is the Cenomanian extinction event at 91 Ma, which has no obviously associated continental flood basalt. Large basalt flows with possible start dates of 110 ± 10 Ma and 80 ± 10 Ma, however, have been identified in the western Pacific Ocean (*64*). Thus, there is some evidence for extensive basaltic volcanism at about 90 Ma (*65*).

Possible Periodicity

The question of possible periodicity in the flood basalt record was raised by Vogt (*57*), who suggested cycles of 50 to 60 million years that might be associated with the geologic periods. On the basis of the present compilation of age data, we have performed a time-series spectral analysis to try to answer this question more quantitatively.

Assuming a periodic delta-function response to the unknown input signal, the nonparametric method of Stothers (*66*) can be used to search for significant periods in the series of dates. Because of the sensitivity (in any method) of the absolute heights of the spectral peaks to modest errors in the dates, we maintained only a simple count of the number of times the highest spectral peak occurred at the same period for 1000 time series in which the date for each episode was randomly selected from the age range indicated for that particular episode in Table 1. To avoid spurious periods that may arise from both the high-frequency noise in the data and the low-frequency cutoff to the data string from the finite record length, we sampled only the period range 18 to 100 million years.

A histogram of our results based on all 11 flood basalt episodes (Fig. 2) suggests that if there is any periodicity in this record the most likely period is either around 22 to 26 million years or around 31 million years. If an additional flood basalt at 90 ± 10 Ma is introduced into the record, or if the Siberian flood basalt at 250 ± 10 Ma (which belongs to a less well dated and possibly

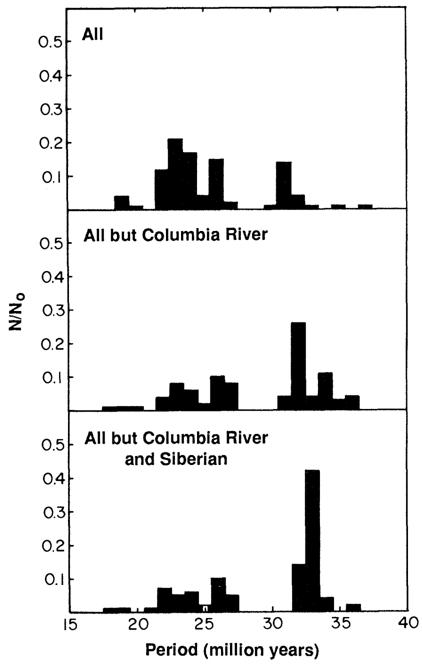

Fig. 2. Frequency diagram of the periods at which the highest spectral peak occurs, for 1000 pseudo-random time series of flood basalt initiation dates (the dates of Table 1 were randomized within their estimated errors). "All" refers to all 11 flood basalts of Table 1.

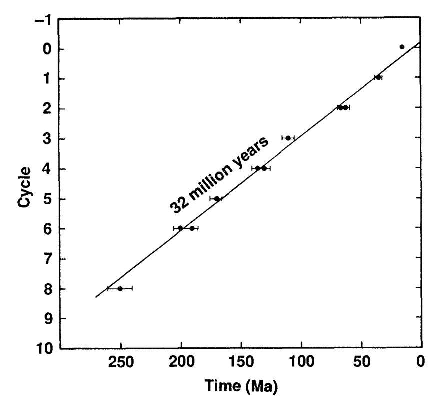

Fig. 3. Time-cycle diagram for flood basalt episodes, with a line showing the best-fit period of 32 million years based on the results of Fig. 2. A bar indicates the probable range of accidental and systematic errors for the initiation date of the episode.

incomplete part of the record before 200 Ma) is omitted, the histogram is essentially unchanged. Because the Columbia River basalts seem to have erupted in other than a continental rift-related setting, perhaps they do not belong to the present class of eruptions and should be omitted. If so, the most probable period becomes 32 million years (Fig. 2). Even if they are classical flood basalts and constitute part of the irregularity in what is only a quasi-periodic phenomenon, they were omitted in an effort to improve the best-fit (though approximate) period because their age departs significantly from a mean cycle line (Fig. 3) and thus disproportionately skews the analysis for periodicity. If both the Columbia River and Siberian basalts are omitted, the most probable period becomes even more marked and shifts slightly to 33 million years (Fig. 2).

Although these tests should not be interpreted as proving that a physical periodicity is present in the data, they do suggest the possible existence of a quasi-period of 32 ± 1 (estimated error of the mean) million years. The most recent epoch of the fitted mean cycle (Fig. 3) is then 4 ± 4 Ma, somewhere close to the present time. The fact that the Columbia River basalts occurred 17 million years ago probably indicates that the cyclic mechanism (if there is one) is not strictly periodic. Independently dated sets of other types of geological phenomena have previously been analyzed, and the results suggest quasi-periods of a similar length: 34 ± 3 million years for alkalic and silicic volcanism, 33 ± 3 million years for active tectonism, 33 ± 3 million years for low sea levels, and 30 ± 2 million years for clusters of magnetic reversals (*67, 68*). Mass extinctions, too, seem to show a periodicity of 29 ± 3 million years (*59, 62, 63*). If these various phenomena are physically related, they could share a common period of 31 million or 32 million years. A quasi-period of 31 ± 3 million years has also been independently reported for terrestrial impact cratering (*63, 67, 69*). Although phase information is rather uncertain, the phases seem to be the same within the errors, and thus the most recent epoch is formally close to the present time.

Origin of Flood Basalts

The origin of flood basalt eruptions has been extensively debated. Mechanisms related to mantle plume activity, which may be quasi-periodic, have been commonly proposed (*70*), but what triggers the disturbances of the mantle is unknown. A possible energy source is impact of comets (or asteroids) (*67, 71*), a mechanism that is supported by recent modeling of impact cratering (*72*) and of the dynamics of quasi-periodic showers of comets (*63, 73*). Impacts may, as a result, have led to mass extinctions through direct atmospheric and marine disturbances (*74*) and indirectly through the effects of prolonged flood basalt volcanism.

In view of the suggested temporal association between the initiations of flood basalt episodes and mass extinctions of life, there is probably a physical connection between the two. Calculations have shown that during the eruption of a major basaltic lava flow, convective plumes rising above vigorous fire fountains would probably inject into the stratosphere a large mass of sulfur-rich gases that are precursors of sulfuric acid aerosols (*75*). Stratospheric winds could then transport these aerosols hemispherically or even globally, with probably severe climatic and biological consequences (*57, 58, 75*). These proposed effects of "impact volcanism" can perhaps explain many of the characteristics of environmental crises at important geological boundaries.

REFERENCES AND NOTES

1. Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets* (Pergamon, New York, 1981).
2. K. Burke and W. S. F. Kidd, *Geol. Assoc. Can. Spec. Pap.* **20**, 503 (1980).
3. W. D. West, *Proc. Indian Natl. Sci. Acad.* **51A**, 465 (1985).
4. R. A. Scrutton, *Geol. Mag.* **110**, 227 (1973).
5. G. B. Dalrymple and M. A. Lanphere, *Potassium-Argon Dating* (Freeman, New York, 1969).
6. G. Faure, *Principles of Isotope Geology* (Wiley, New York, ed. 2, 1986).
7. P. R. Hooper, *Science* **215**, 1463 (1982).
8. N. D. Watkins and A. K. Baksi, *Am. J. Sci.* **274**, 148 (1974).
9. J. F. Evernden and G. T. James, *ibid.* **262**, 945 (1964); G. B. Dalrymple, A. Cox, R. R. Doell, C. S. Grommé, *Earth Planet. Sci. Lett.* **2**, 163 (1967); J. Gray and L. R. Kittleman, *Am. J. Sci.* **265**, 257 (1967); D. A. Holmgren, in *Proceedings of the Second Columbia River Basalt Symposium*, E. H. Gilmour and D. Stradling, Eds. (Eastern Washington State College Press, Cheney, WA, 1970), pp. 189–200; P. D. Snavely, Jr., N. S. MacLeod, H. C. Wagner, *Geol. Soc. Am. Bull.* **84**, 387 (1973); R. J. Bottomley and D. York, *Earth Planet. Sci. Lett.* **31**, 75 (1976); J. F. Sutter, *Isochron/West* **21**, 15 (1978); E. H. McKee, P. R. Hooper, W. D. Kleck, *ibid.* **31**, 31 (1981); D. R. Lux, *ibid.* **33**, 27 (1982); P. E. Long and R. A. Duncan, *Eos* **64**, 90 (1983).
10. S. M. Behre, B. Desta, M. Nicoletti, M. Tefera, *J. Geol. Soc. London* **144**, 213 (1987).
11. P. Mohr, *Nature* **303**, 577 (1983).
12. G. Capaldi, P. Manetti, G. B. Piccardo, G. Poli, *Neues Jahrbuch Miner. Abh.* **156**, 207 (1987).
13. R. Grasty, J. A. Miller, P. A. Mohr, *Bull. Geophys. Obs. Haile Selassie Univ.* **6**, 97 (1963).
14. E. Abbate and M. Sagri, in *Geodynamic Evolution of the Afro-Arabian Rift System* (Accademia Nazionale dei Lincei, Rome, 1980), pp. 219–227.
15. G. H. Megrue, E. Norton, D. W. Strangway, *J. Geophys. Res.* **77**, 5744 (1972).
16. S. R. Carter, N. M. Evensen, P. J. Hamilton, R. K. O'Nions, *Nature* **281**, 28 (1979).
17. R. S. White *et al.*, *ibid.* **330**, 439 (1987).
18. A. L. Evans, F. J. Fitch, J. A. Miller, *J. Geol. Soc. London* **129**, 419 (1973).
19. A. E. Mussett, P. Dagley, R. R. Skelhorn, *ibid.* **137**, 349 (1980); A. E. Mussett, *ibid.* **143**, 887 (1986).
20. D. H. Tarling and N. H. Gale, *Nature* **218**, 1043 (1968); A. E. Mussett, G. C.

Brown, M. Eckford, S. R. Charlton, *Geophys. J. R. Astron. Soc.* **30**, 405 (1972); P. Mohr, A. E. Mussett, P. S. Kennan, *Geol. J.* **19**, 1 (1984).
21. D. B. Clarke and B. G. J. Upton, *Can. J. Earth Sci.* **8**, 248 (1971).
22. R. D. Beckinsale, R. N. Thompson, J. J. Durham, *J. Petrol.* **15**, 525 (1974).
23. L. M. Larsen and W. S. Watt, *Earth Planet. Sci. Lett.* **73**, 105 (1985).
24. W. Lowrie and W. Alvarez, *Geology* **9**, 392 (1981); D. V. Kent and F. M. Gradstein, in *The Geology of North America*, vol. M, *The Western North Atlantic Region*, P. R. Vogt and B. E. Tucholke, Eds. (Geological Society of America, Boulder, CO, 1986), pp. 45–50.
25. W. B. Harland *et al.*, *A Geologic Time Scale* (Cambridge Univ. Press, Cambridge, 1982).
26. V. Courtillot *et al.*, *Earth Planet. Sci. Lett.* **80**, 361 (1986) (see also the references therein).
27. A similar compilation to that in (*26*) is in P. O. Alexander, in *Deccan Volcanism*, K. V. Subbarao and R. N. Sukheswala, Eds. (Geological Society of India, Bangalore, 1981), pp. 244–258. Recently, 13 good Ar-Ar plateau ages ranging from 68 to 63 Ma have been reported [R. A. Duncan and D. G. Pyle, *Nature* **333**, 841 (1988); V. Courtillot *et al.*, *ibid.*, p. 843].
28. W. D. West, in *Deccan Volcanism*, K. V. Subbarao and R. N. Sukheswala, Eds. (Geological Society of India, Bangalore, 1981), pp. 277–278.
29. I. Kaneoka, *Earth Planet. Sci. Lett.* **46**, 233 (1980).
30. Uncertainties of the paleomagnetic date of the Deccan Traps have recently been debated by several authors [A. K. Baksi, *Geology* **15**, 147 (1987); H. Wensink, *Earth Planet. Sci. Lett.* **85**, 326 (1987); V. Courtillot, D. Vandamme, J. Besse, *ibid.* **86**, 122 (1987)].
31. A. K. Baksi, T. R. Barman, D. K. Paul, E. Farrar, *Chem. Geol.* **63**, 133 (1987).
32. I. McDougall and M. W. McElhinny, *Earth Planet. Sci. Lett.* **9**, 371 (1970).
33. M. V. N. Murthy, in *Deccan Volcanism*, K. V. Subbarao and R. N. Sukheswala, Eds. (Geological Society of India, Bangalore, 1981), pp. 93–100.
34. J. K. Agrawal and F. A. Rama, *Proc. Indian Acad. Sci.* **84A**, 157 (1976).
35. G. Bellieni *et al.*, *J. Petrol.* **25**, 579 (1984).
36. K. M. Creer, J. A. Miller, A. G. Smith, *Nature* **207**, 282 (1965); G. Amaral, U. G. Cordani, K. Kawashita, J. H. Reynolds, *Geochim. Cosmochim. Acta* **30**, 159 (1966); I. McDougall and N. R. Rüegg, *ibid.*, p. 191; P. Vandoros, N. R. Rüegg, U. G. Cordani, *Earth Planet. Sci. Lett.* **1**, 449 (1966); A. J. Melfi, *Geochim. Cosmochim. Acta* **31**, 1079 (1967); U. G. Cordani, P. L. P. Sartori, K. Kawashita, *Ann. Acad. Brasil. Cienc.* **52**, 811 (1980).
37. G. Siedner and J. G. Mitchell, *Earth Planet. Sci. Lett.* **30**, 292 (1976).
38. M. U. Umpierre and M. Halpern, *Rev. Assoc. Geol. Argentina* **26**, 133 (1971).
39. G. Siedner and J. A. Miller, *Earth Planet. Sci. Lett.* **4**, 451 (1968).
40. A. Gidskehaug, K. M. Creer, J. G. Mitchell, *Geophys. J. R. Astron. Soc.* **42**, 1 (1975).
41. A. E. Moore, *Earth Planet. Sci. Lett.* **31**, 291 (1976).
42. D. H. Elliot, in *Proceedings of the Second Columbia River Basalt Symposium*, E. H. Gilmour and D. Stradling, Eds. (Eastern Washington State College Press, Cheney, WA, 1970), pp. 301–325.
43. W. Compston, I. McDougall, K. S. Heier, *Geochim. Cosmochim. Acta* **32**, 129 (1968).
44. I. McDougall, *J. Geophys. Res.* **68**, 1535 (1963).
45. R. J. Fleck, J. F. Sutter, D. H. Elliot, *Geochim. Cosmochim. Acta* **41**, 15 (1977).
46. P. R. Kyle, D. H. Elliot, J. F. Sutter, in *Gondwana Five*, M. M. Cresswell and P. Vella, Eds. (Balkena, Rotterdam, 1981), pp. 282–287; W. C. McIntosh, P. R. Kyle, E. M. Cherry, H. C. Noltimer, *Ant. J. U.S.* **17**, 20 (1982); D. H. Elliot and K. A. Folland, *Ant. Res. Ser.* **46**, 279 (1986); W. C. McIntosh, P. R. Kyle, J. F. Sutter, *ibid.*, p. 289.
47. I. McDougall, *Nature* **190**, 1184 (1961).
48. P. W. Schmidt and I. McDougall, *J. Geol. Soc. Australia* **25**, 321 (1977).
49. F. J. Fitch and J. A. Miller, *Bull. Volcanol.* **35**, 64 (1971). For a general overview of Karroo volcanism, see J. W. Bristow and E. P. Saggerson, *Geol. Rundsch.* **72**, 1015 (1983) and A. J. Erlank, Ed., *Geol. Soc. S. Afr. Spec. Publ.* **13**, 1 (1984).
50. D. I. Gough, A. Brock, D. L. Jones, N. D. Opdyke, *J. Geophys. Res.* **69**, 2499 (1964); A. J. Burger and F. J. Coertze, *Bull. Geol. Surv. S. Afr.* **58**, 1 (1973); W. Jaritz, H. Kreuzer, P. Muller, W. Harre, *Geol. Jahrb.* **26**, 147 (1977); R. W. Cleverly, thesis, Oxford University (1977). See also a similar compilation to ours [L. Cahen *et al.*, Eds., *The Geochronology and Evolution of Africa* (Clarendon, Oxford, 1984)].
51. A. R. Philpotts and A. Martello, *Am. J. Sci.* **286**, 105 (1986).
52. R. E. Bolich, M. G. Bevis, J. J. Won, R. V. Fodor, *Geol. Soc. Am. Abstr. Progr.* **17**, 527 (1985); J. H. McBride, K. D. Nelson, L. D. Brown, D. M. Wille, *ibid.* **18**, 687 (1986); P. R. May, *Geol. Soc. Am. Bull.* **82**, 1285 (1971).
53. G. P. Erickson and J. L. Kulp, *Geol. Soc. Am. Bull.* **72**, 649 (1961); C. M. Carmichael and H. C. Palmer, *J. Geophys. Res.* **73**, 2811 (1968); J. DeBoer, *Geol. Soc. Am. Bull.* **79**, 609 (1968); R. L. Armstrong and J. Besancon, *Eclogae Geol. Helv.* **63**, 15 (1970); D. Corrigan, thesis, University of Rhode Island (1972); R. H. Reesman, C. F. Filbert, H. W. Krueger, *Geol. Soc. Am. Abstr. Progr.* **5**, 211 (1973); R. D. Dallmeyer, *Geology* **3**, 243 (1975); A. Hayatsu, *Can. J. Earth Sci.* **16**, 973 (1979); J. F. Sutter and T. E. Smith, *Am. J. Sci.* **279**, 808 (1979); J. P. Hodych and A. Hayatsu, *Can. J. Earth Sci.* **17**, 491 (1980); D. E. Seidemann, W. D. Masterson, M. P. Dowling, K. K. Turekian, *Geol. Soc. Am. Bull.* **95**, 494 (1984); J. F. Sutter, *U.S. Geol. Survey Circ.* **946**, 110 (1985); D. E. Seidemann, *Chem. Geol. (Isotope Geoscience Section)* **72**, 37 (1988). See also J. G. McHone and J. R. Butler, *Geol. Soc. Am. Bull.* **95**, 757 (1984). Related diabase dikes and sills in northwestern Liberia show K-Ar ages ranging from 192 to 173 Ma [G. B. Dalrymple, C. S. Grommé, R. S. White, *ibid.* **86**, 399 (1975)].
54. D. J. DePaolo and G. J. Wasserburg, *Proc. Natl. Acad. Sci. U.S.A.* **76**, 3056 (1979).
55. W. T. Holser and M. Magaritz, *Modern Geol.* **11**, 155 (1987).
56. Y. I. Dmitriyev and A. I. Guseva, in *Magmatism and Ore Formation* (Akademiya Nauk Petrographical Committee, Moscow, 1974), pp. 135–153 (in Russian).
57. P. R. Vogt, *Nature* **240**, 338 (1972).
58. J. Campsie, G. L. Johnson, J. E. Jones, J. E. Rich, *Eos* **65**, 796 (1984); D. M. McLean, *Cretaceous Res.* **6**, 235 (1985); W. J. Morgan, *Eos* 67, 391 (1986); M. R. Rampino and R. B. Stothers, *ibid.*, p. 1247; C. B. Officer, A. Hallam, C. L. Drake, J. D. Devine, *Nature* **326**, 143 (1987).
59. D. M. Raup and J. J. Sepkoski, Jr., *Science* **231**, 833 (1986).
60. G. S. Odin, Ed., *Numerical Dating in Stratigraphy* (Wiley, New York, 1982); A. R. Palmer, Decade of North American Geology (DNAG) Compiler, *Geology* **11**, 503 (1983). Another recent time scale [N. J. Snelling, Ed., *The Chronology of the Geological Record* (Blackwell, Oxford, 1985)] is largely a compromise among several time scales proposed previously. The use of an average of different time scales is advocated by U. Bayer, *Geol. Rundsch.* **76**, 485 (1987).
61. A. Hoffman and J. Ghiold, *Geol. Mag.* **122**, 1 (1985); J. A. Kitchell, *Paleoceanography* **2**, 473 (1987).
62. D. M. Raup and J. J. Sepkoski, Jr., *Proc. Natl. Acad. Sci. U.S.A.* **81**, 801 (1984).
63. M. R. Rampino and R. B. Stothers, *Nature* **308**, 709 (1984).
64. D. K. Rea and T. L. Vallier, *Geol. Soc. Am. Bull.* **94**, 1430 (1983).
65. In South-West Africa, a brief period of alkaline intrusions occurred around 90 Ma. In the same region, other alkaline intrusions occurred around 130, 60, and 37 Ma (*41*) and therefore correspond to three of the known flood basalt episodes in Table 1. Similar alkaline intrusions have occurred in Brazil, with dates of about 135, 110, and 90 Ma [G. Amaral, J. Bushee, U. G. Cordani, K. Kawashita, J. H. Reynolds, *Geochim. Cosmochim. Acta* **31**, 117 (1967); N. Herz, *Geol. Soc. Am. Bull.* **88**, 101 (1977)].
66. R. B. Stothers, *Astron. Astrophys.* 77, 121 (1979). The present statistical approach of comparing the highest spectral peaks in many randomly perturbed time series has been validated through extensive numerical testing [R. B. Stothers, *Nature* **317**, 338 (1985)].
67. M. R. Rampino and R. B. Stothers, *Science* **226**, 1427 (1984).
68. D. M. Raup, *Nature* **314**, 341 (1985); R. B. Stothers, *ibid.* **322**, 444 (1986).
69. W. Alvarez and R. A. Muller, *ibid.* **308**, 718 (1984); J. S. Trefil and D. M. Raup, *Earth Planet. Sci. Lett.* **82**, 159 (1987); R. B. Stothers, *Observatory* **108**, 1 (1988).
70. V. Courtillot and J. Besse, *Science* **237**, 1140 (1987); K. G. Cox, *J. Petrol.* **21**, 629 (1980).
71. E. J. Öpik, *Ir. Astron. J.* **5**, 34 (1958); R. S. Dietz, *Nature* **197**, 39 (1963); H. C. Urey, *ibid.* **242**, 32 (1973); C. K. Seyfert and J. G. Murtaugh, *Geol. Soc. Am. Abstr Progr.* **9**, 1168 (1977); S. V. M. Clube and W. M. Napier, *Earth Planet. Sci. Lett.* **57**, 251 (1982).
72. M. R. Rampino, *Nature* **327**, 468 (1987).
73. R. Smoluchowski, J. N. Bahcall, M. S. Matthews, Eds., *The Galaxy and the Solar System* (Univ. of Arizona Press, Tucson, 1986).
74. W. Alvarez, *Eos* **67**, 649 (1986); P. Hut *et al.*, *Nature* **329**, 118 (1987); L. W. Alvarez, *Phys. Today* **40**, 24 (July 1987).
75. R. B. Stothers, J. A. Wolff, S. Self, M. R. Rampino, *Geophys. Res. Lett.* **13**, 725 (1986).
76. A listing of K-Ar and Ar-Ar ages that were compiled for this study will be provided by specific request to M.R.R. We thank A. K. Baksi, V. Courtillot, R. A. Duncan, E. I. Erlich, C. J. Hawkesworth, P. R. Hooper, S. Self, J. A. Wolff, C. A. Wood, and anonymous reviewers for helpful information. The Center for Global Habitability at Columbia University provided support for M.R.R.