Episodes of Flood-Basalt Volcanism Defined by $^{40}Ar/^{39}Ar$ Age Distributions: Correlation with Mass Extinctions?

BRUCE M. HAGGERTY

Recent interest in flood basalt volcanism has highlighted the need for accurate age constraints on continental flood basalts (CFBs). Unfortunately, many basalt groups lack reliable age determinations. To overcome this problem, we have compiled all published $^{40}Ar/^{39}Ar$ and U/Pb age determinations (205 separate dates). From these raw data points, probability functions for the age of the basalt were constructed with standard statistical methods, and they were used to identify what we consider to be the "best" inception age for the basalt. These age distributions and additional evidence suggest that in most cases eruptions of the bulk of the flood basalts took place in <1-3 Myr. The initiation ages computed from the data set were tested for possible temporal correlation to mass extinction events using an established cross-correlation method. A correlation was detected at the 97% confidence level. This analysis is interpreted as strong evidence for a causal relationship between extinctions, flood basalts and/or other geological phenomena such as concurrent large impact events or mantle plume outbreaks. Fourier analysis was used to provide a quantitative test for periodicity in the new data set. Evidence was detected for a quasi-period of 23 Myr, but Monte Carlo testing revealed that this period had a relatively low confidence level. These results may be indicative of a combination of a weak periodic signal and random events.

Introduction

Continental flood basalts, with extrusion volumes estimated to have been ~$2x10^5$ to >$2x10^6$ km^3, represent the largest outpourings of mafic magma on the continents, an order of magnitude or more greater in volume than the next largest provinces of basaltic eruptions [Rampino and Stothers, 1988; White and McKenzie, 1989; Coffin and Eldholm, 1993a]. Oceanic flood basalts of comparable volume are also known, and continental and oceanic examples are grouped together as Large Igneous Provinces (LIPs) [Coffin and Eldholm, 1993a,b]. Recent studies suggest that eruption of most of the volume of the basaltic magma may take place in a few hundred thousand to one or two million years (eruption rates >1.5 km^3 yr^{-1}) [Courtillot et al., 1986; Renne and Basu, 1991; Baksi and Farrar, 1990; Campbell et al., 1993; Holbrook and Kelemen, 1993], and that volumes of mafic magma considerably larger than that extruded were emplaced concurrently as intrusives in the crust [Coffin and Eldholm, 1993a,b].

Rampino and Stothers (1988) used histograms of more than 900 age determinations (mostly K/Ar and some $^{40}Ar/^{39}Ar$ ages) to produce best estimates of the initiation times of ten recognized continental flood basalt (CFB) eruptions of the last 250 Myr. Stratigraphic, paleomagnetic, and other age data were used as an adjunct to the K/Ar and $^{40}Ar/^{39}Ar$ age determinations (see also [Stothers, 1993; Rampino, 1993; Courtillot, in press]). They found that the age-data histograms, composed largely of K/Ar age determinations, typically displayed an asymmetric appearance, with a few older ages, a relatively sharp increase in the number of ages climbing to a maximum, and an erratically decreasing tail of still-younger ages. Our results confirmed this pattern, and distributions of $^{40}Ar/^{39}Ar$ had a similar appearance.

The K/Ar technique is known to be plagued by problems of Ar loss (giving anomalously young dates) and Ar retention (leading to some anomalously old dates). Analysis suggested that the true initiation date of the massive eruptions was best determined by the segment of the distribution that exhibited a steep slope in a rapid rise to the maximum of the age histograms [Rampino and Stothers, 1988]. Conservative error estimates ranged from ±1 million years for the Columbia River Basalts (17±1 Myr) to ±10 Myr for the Siberian Traps (250±10 Myr) (full range error), with the initiation times of most CFBs having estimated errors of about ±5 Myr (the size of the bins used in the age-data histograms) (Table 1). Paleozoic CFBs seem to be either relatively rare and/or poorly exposed; we point out, however, the Panjal Traps of the NW Himalayas (Early Permian), the Clyde Plateau Lavas of Scotland (Early Carboniferous), and the Antrim Basalts of Australia (Cambrian) as possible examples, and we are now in the process of compiling available age data on pre-Mesozoic flood basalts.

Since the compilation of data published in Rampino and Stothers (1988), an additional continental basaltic province, the Madagascar Basalts, estimated from its stratigraphic context to be of Mid-Cretaceous (Cenomanian to Turonian) age (~90±5 Myr), is now believed to have been much more widespread [Macdougall et al., 1992] and is included here as a true CFB. Recent K/Ar dating of dikes related to the Madagascar basalts gave a mean age of 94.5±1.2 (1σ) Myr [Storevedt et al., 1992] (see below for more recent $^{40}Ar/^{39}Ar$ age determinations).

Large oceanic plateaus (e.g., the Ontong-Java Plateau) are interpreted by some as the result of oceanic flood basalt eruptions [Coffin and Eldholm, 1993], but only a few Mesozoic examples are reasonably well dated (see below). The Wrangellia Flood Basalt in British Columbia (possibly largely oceanic in origin) has been identified and dated stratigraphically as close to the Ladinian-Carnian boundary (~230±5 Myr), but no radiometric dates are available [Richards et al., 1991]. The very thick and voluminous (>250,000 km^3) Crescent Basalts of western Washington State and British Columbia, with $^{40}Ar/^{39}Ar$ ages of ~58 to 55 Myr and ~50 Myr respectively, may be related to hotspot volcanism [Babcock et al., 1992].

The conventional K-Ar method of dating depends on the assumptions that the sample contained no argon at the time of formation and that subsequently all radiogenic argon produced within it was quantitatively retained. Problems of argon loss and excess initial argon can be overcome by using several $^{40}Ar/^{39}Ar$ dating methods [Faure, 1986]. In these

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BRUCE M. HAGGERTY is a first-year student attending Harvard College. He completed the research described in this article under the supervision of Dr. Michael Rampino at New York University, with whom he has worked for four years and with whom he has coauthored a number of articles. Mr. Haggerty was honored as the 4th place winner in the Westinghouse Science Talent Search for this work.

Table 1. Continental flood basalts and mass extinctions.

Continental Flood Basalts	*K/Ar* (Myr)*	*^{40}Ar/^{39}Ar (Myr)*	*Extinction Boundaries*	*(Myr)*
Columbia River	17±1	16.2±1	Lower/Mid-Miocene	14±3
Ethiopian	35±2	(36.9±0.9)	Eocene/Oligocene$^{Ir,\ mt/t,q}$	36±1
North Atlantic	62±3	60.5	Late Paleocene	59±1
Deccan	66±2	65.5±2.5	Cretaceous/Tertiary$^{Ir,mt/t,q}$	65±1
Madagascar	94±1	87.6±0.6	Cenomanian/Turonian^{Ir}	91±1
Rajmahal	110±5	116±1	Aptian/ Albian	113±3
Serra Geral	130±5	132±1	Jurassic/Cretaceous	137±7
Antarctic	170±5	176±1	Bajocian/Bathonian	173±3
Karoo	190±5	190±3	Pliensbachian	193±3
Newark	200±5	201±1	end-Triassic^{q,Ir}	211±8
Siberian	250±10	250±1	Permian/Triassic$^{Ir?}$	250±1

*K/Ar age data compiled in Rampino and Stothers (1988), with additional data on Madagascar Basalts.
Several boundaries show stratigraphic evidence of large-body impact—shocked quartz (q), microtektites/tektites (mt/t), and/or iridium (Ir).

methods, a portion of ^{39}K is converted to ^{39}Ar by neutron bombardment. The ^{40}Ar/^{39}Ar methods can be affected by problems of excess and inherited argon, and loss of ^{39}Ar by recoil in some samples, and only samples giving well-defined age plateaus have been used in the present compilation. Problems involving laboratory intercalibration and the age of neutron-fluence monitors (standards) used to calibrate ages can affect the ^{40}Ar/^{39}Ar age determinations, and reported dates may contain systematic errors that are not reflected in the formal analytical error estimates [Renne et al., 1994]. Recent studies have shown that compilations of ^{40}Ar/^{39}Ar age determinations can be used to improve the resolution of dating of episodes of basaltic volcanism [Vandamme et al., 1991; Sebai et al., 1991; Heimann et al., 1994]. We here utilize published ^{40}Ar/^{39}Ar dates and other ancillary information to obtain a "best" date for each flood basalt episode (Table 1).

Methods

We compiled histograms of 205 ^{40}Ar/^{39}Ar ages by constructing normal (Gaussian) probability curves centered on each individual analysis, using the stated analytical error to define the standard deviation. The sum of these curves defined a probability distribution for the age of the basalt. These "Gaussian histograms" have been used before [Sebai et al., 1991] on individual basalt provinces with good results. The area under the Gaussian curve for each individual sample is the same, and the height is inversely proportional to the standard deviation. Thus, peaks in the summed curve represent either more precise analyses or ages with several well-constrained dates. The highest point in the probability distribution was our primary indicator of basalt age. The median of each sample was determined by integrating the Gaussian curves and was used as a secondary measure of basalt age (for those age distributions that did not contain a single well defined peak). A few published age determinations did not indicate whether the stated errors were 1σ or 2σ. In these cases, to be conservative, we took the given error as a 1σ value when constructing the probability distributions.

In some cases, recent U/Pb age determinations on individual baddeleylite and zircon grains were available that highlighted recognized problems with published ^{40}Ar/^{39}Ar dates (e.g., large range of ages). In these instances, the U/Pb dates were found to be good indicators of the "best" age of the eruption. Paleomagnetic chronology was used as an important adjunct to the radiometric and isotopic dating, but large dating uncertainties over some intervals restricted its usefulness. Stratigraphic studies also helped to constrain the ages of the basalts.

The data set used here was compiled from a number of sources and was screened to avoid those dates which were of questionable accuracy, e.g., poor age plateaus in ^{40}Ar/^{39}Ar step-heating age determinations, disagreement in replicate analyses [Vandamme et al., 1991]. In order to avoid unconscious bias, we have taken care to exclude only those analyses which clearly suffer from reliability problems. However, because of the wide variance between analytical techniques, we found it impossible to define more than a loose set of criteria for acceptance into the data set.

In most cases, we consider the best estimate of the initiation time for a given basalt group to be the highest point in the probability distribution. However, the probability distributions for some of the basalt groups contained multiple peaks of similar magnitude (e.g., Deccan; Fig. 1d). The median age from the distribution appears to provide the best estimate for these basalts. The presence of multiple peaks is usually indicative of reheating events or of multiple eruption pulses, but in some cases appears due to Ar loss/retention in one (or more) of the studies.

Results

Columbia River Basalts. Our compilation contains a total of seven ^{40}Ar/^{39}Ar age determinations of the Columbia River Basalts [Lux, 1982; Baksi and Farrar, 1990], ranging from 17.1 to 15.6 Myr, which give a probability distribution with a mean of 16.0 Myr, a median of 15.9 Myr and a well defined peak age of 16.1 Myr (Fig. 1a). Analyses of K/Ar and ^{40}Ar/^{39}Ar age determinations suggest that ~90% of the lavas of the Columbia River province was erupted during the interval between 15.9 Myr and 16.1 Myr [Rampino and Stothers, 1988; Baksi and Farrar, 1990; Baksi, 1990].

Bottomly and York (1976) presented additional whole rock ^{40}Ar/^{39}Ar ages that range from 12.7±0.3 to 16.0±0.7 Myr

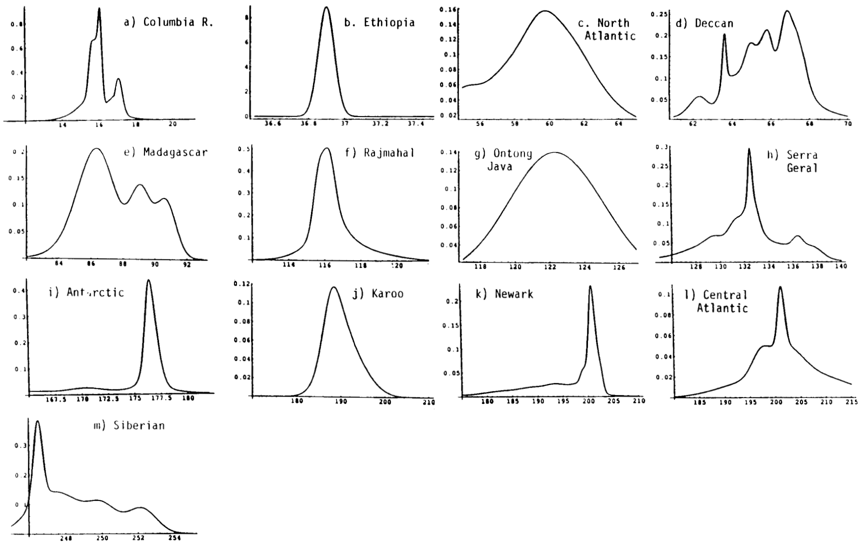

Figure 1. Probability distributions for regional basalt groups.

(1σ), but their analyses utilized the technique of grinding the samples to release atmospheric argon and yielded generally poor plateaus. These age determinations were not included in our compilation and analysis.

Ethiopian Basalts. ^{40}Ar/^{39}Ar age determinations are not yet available for mafic rocks of the Ethiopian Basalt Province. Rampino and Stothers (1988) estimated a initiation date of 35±2 Myr based on a histogram of 122 K/Ar age determinations. Recently, a widespread silicic unit, the Amaro Tuff, has been ^{40}Ar/^{39}Ar dated at 36.9±0.9 Myr (1σ) [Ebinger et al., 1993] (Fig. 1b). However, the tuff rests upon 0.5 to 1 km of flood basalts dated by conventional K/Ar methods between 44.9 and 37.0 Myr. This suggests either that the flood basalts began ~45 Myr ago, or that the older K/Ar age determinations are problematic. If the latter is correct, then the bulk of the Ethiopian CFB eruption might have occurred close to the 36.9 Myr age ^{40}Ar/^{39}Ar age determination of the tuff. K/Ar age determinations of related flood basalts in Yemen give ages between ~30 and 26 Myr [Manetti et al., 1991]. Clearly, more ^{40}Ar/^{39}Ar age determinations are needed to resolve these dating problems.

North Atlantic Basalts. There are ten published ^{40}Ar/^{39}Ar age determinations performed specifically on mafic rocks of the North Atlantic Basalt Province (NABP) in our compilation [Mohr et al., 1984; Evans et al., 1973; Musset, 1986; Musset et al., 1980; Musset, 1980]. The NABP consists of the British-Tertiary Province, the East Greenland Basalts, and the West Greenland Basalts. Ranging from 62.5 to 55 Myr, the dates yield a distribution with a mean age of 59.5 Myr, a median of 59.6 Myr, and a peak age of 59.8 Myr (Fig. 1c). The broad peak in the probability distribution reflects a large range of apparent initiation ages for the North Atlantic Basalts.

Mussett et al. (1988), using a combination of Rb-Sr isochron dates, ^{40}Ar/^{39}Ar plateau ages, and conventional K/Ar dates (for those analyses that yielded concordant values from different types of rocks or minerals), estimated a similar interval of ~63 to 52 Myr, with a peak at 59 Myr, for the British-Tertiary Province of the NABP.

The results of magnetic studies suggest that volcanism in the British Tertiary Province began in Magnetic Chron 26R (~62 to 59 Myr ago using Harland et al, 1989 time scale, or ~63 to 61 Myr using Berggren et al., 1985), which is in agreement with stratigraphic studies in the North Sea, where the earliest pyroclastic activity (associated with the British-Tertiary volcanism) occurred in calcareous nanoplankton Zone NP6 [Knox and Morton, 1988]. The earliest magnetic anomaly in the North Atlantic basin is Anomaly 24 (~54-55 Myr) [Fram and Lesher, 1993].

The East Greenland Basalts of the NABP were apparently erupted during Chron 24R (~57 to 55 Myr in Harland et al., or ~59 to 56 Myr in Berggren et al.) [Morton et al., 1988; Tarling et al., 1988; Upton, 1988; White and McKenzie, 1989; Coffin and Eldholm, 1993]. The most recent ^{40}Ar/^{39}Ar ages for the East Greenland Basalts are 58.7±1.4 Myr (2σ) for a flow in the lower series, and 56.7±0.7 and 56.6±1.9 Myr (2σ) for late stage dikes that cut the upper series of lava flows [Upton and Rex, unpublished data].

In West Greenland, marine mudstones intercalated with volcanic hyaloclastites were deposited in nanoplankton zones NP4 to NP8. The lowest horizon of normally magnetized sub-aerial lavas are placed in polarity chron 27N, whereas the bulk of the lavas are reversely magnetized, and placed in Chrons 26R and 25R [Larsen et al., 1992; Piasecki et al., 1993]. These constraints place the West Greenland eruptions between ~62-58 Myr or ~63-59 Myr, depending on the magnetic polarity timescale adopted.

Deccan Traps. We have compiled 37 ^{40}Ar/^{39}Ar age determinations for the Deccan Basalts [Kaneoka, 1980; Duncan and Pyle, 1988; Courtillot et al., 1988; Shaw et al., 1990; Kunk (pers. comm. in Vandamme et al., 1988); Pande et al., 1988; Venkatesan et al., 1993; Baksi, 1994], and derive a mean age of 65.7 Myr, a median of 65.8 Myr and a distribution with the highest peak at 66.9 Myr, with smaller peaks at 62.4, 63.7 and 65.7 Myr (Fig. 1d). This is in agreement with Vandamme et al. (1991), who reviewed all published ^{40}Ar/^{39}Ar age determinations for the Deccan Basalts; using a total of 22 high-quality analyses they derived a weighted mean age of 65.5±2.5 (1σ) Myr. In the Seychelles Islands, dikes of olivine tholeitic basalts and gabbros very similar to the Deccan Basalts of India [Dickin et al., 1986; Devey and Stephens, 1991] give K-Ar ages of 64.7±1.4 (1σ) Myr.

Several more recent studies have provided additional data. Venkatesan et al. (1993) reported ten ^{40}Ar/^{39}Ar age determinations from the western Ghats with plateau ages ranging from 67.5±0.8 Myr to 62.1±1.0 Myr (2σ). They argued that the lower ~2 km thick reversely magnetized sequence of Deccan flows was erupted close to 67 Myr ago (during Chron 31R). However, plateau ages differ from isochron ages by up to 2.7 Myr and ages are not in stratigraphic order, and were not used in our compilation.

Biotites from alkalic igneous complexes in the Deccan region yield ^{40}Ar/^{39}Ar ages of 68.53±0.16 and 68.57±0.08 Myr (2σ), suggesting that a pulse of alkalic volcanism may have predated the flood basalt eruption. A third complex that intrudes the basalts gives a plateau age of 64.96±0.11 Myr (2σ) [Basu et al., 1993]

Baksi (1994) presented 21 new K/Ar and 15 new ^{40}Ar/^{39}Ar age determinations. The K/Ar ages showed a wide range from 48.1±0.6 to 97.0±0.8 Myr (2σ), but five samples showed good ^{40}Ar/^{39}Ar plateau ages: 65.6±0.6, 65.6±0.5, 65.9±0.4, 64.9±0.5, 64.7±1.1 Myr (2σ). The average of the best plateau ages gives 65.5±0.5 Myr (2σ), which is similar to our compilation results, and results of high-precision ^{40}Ar/^{39}Ar age determinations (65.2±0.5 and 64.7±0.5 Myr (2σ)) on plagioclase separates from samples unaffected by ^{39}Ar recoil problems [Duncan and Pringle, 1991].

The Rajahmundry Traps occupy ~35 km^2 in southeastern India, and have been interpreted as possible intracanyon flows from the main Deccan Province, ~600 km to the east [Baksi et al., 1994]. ^{40}Ar/^{39}Ar age determinations on two samples were problematic, but suggested a weighted plateau age of 64.0±0.5 Myr. They are normally magnetized, and thus are interpreted to have been erupted in Chron 29N [Baksi et al., 1994]. However, stratigraphic studies suggest that the earliest lavas were erupted in the latest Maastrichtian, and straddled the K/T boundary [Jaipraksh et al., 1993; Raju et al., 1994], which would place them in Chron 29R. Recently, an iridium-rich layer (presumably the K/T boundary anomaly) was discovered in intertrappean sediments between the third and fourth lava flows near Kutch at the western boundary of Deccan outcrop [Bhandari et al., 1995].

Madagascar Basalts. The only ^{40}Ar/^{39}Ar age determinations available for the Madagascar Basalts were reported recently by Storey et al. (1993, 1995). Seventeen ^{40}Ar/^{39}Ar age determinations on the Madagascar Basalts and co-erupted rhyolites range from 91 to 84 Myr, with a mean of 87.6±0.6 (1σ) Myr (Fig. 1e). The age distribution produced by these dates has a median at 87.2 Myr, and a highest point at 86.4 Myr, with smaller peaks at 89.1 and 90.6 Myr.

Rajmahal Traps. Early ^{40}Ar/^{39}Ar studies of the Rajmahal Traps suggested a minimum age of ~110 Myr [Dalrymple and Lanphere, 1974; Baksi, 1986]. Baksi et al. (1987) performed eight high-quality K/Ar age determinations on the Rajmahal and related basalts, which (omitting one determination which has clearly suffered Ar loss) gave a mean of 116 Myr. Magnetic studies of the Rajmahal Traps indicate eruption during a normal magnetic interval, most likely the Cretaceous long normal which began about ~120 Myr ago [Sherwood, 1992], and the volcanism has been tied to Early Cretaceous hotspot activity [Curray and Munasinghe, 1991]. Until very recently, only one acceptable ^{40}Ar/^{39}Ar age determination existed for the Rajmahal Traps, which gives an age of 117 ± 1 Myr (2σ) [Baksi, 1988]. Recently, however, a few new age determinations have been reported for the Rajmahal Traps and the possibly related Bunbury Basalts of Western Australia. Pringle et al. (1994) give a ^{39}Ar/^{40}Ar isochron age of 116.2±0.6 Myr (2σ), and spectrum ages of 116.3±0.3 Myr and 115.7±0.3 Myr for samples of the Rajmahal basalts. They also determined an ~130 Myr age for the Bunbury Basalts. The combination of the four ^{39}Ar/^{40}Ar age determinations for the Rajmahal gives a distribution with a peak at 116 Myr (Fig. 1f).

Paraná (Serra Geral) Basalts. Compilation of 39 ^{40}Ar/^{39}Ar age determinations of the Paraná (Serra Geral) Basalts [Renne et al., 1992; Turner et al., 1994] give an age distribution with a mean age of 131.6 Myr, a median at 132.2 Myr and a peak age of 132.6 Myr (Fig. 1h). A recent study using ^{40}Ar/^{39}Ar methods concluded that the basalts at the bottom of the lava pile and those at the top had essentially identical ages, indicating that the bulk of the lava were erupted in a few hundred thousand years at 133 ± 1 (1σ) Myr [Renne et al., 1992]. Results of paleomagnetic analyses also suggest a brief eruption duration (<2 Myr) for the bulk of the basalts [Ernesto and Pacca, 1988].

However, another recent study reported a number of new laser ^{40}Ar/^{39}Ar ages for the Paraná basalts ranging from 138 to 128 Myr, possibly in two age groups, 138-135 Myr and 133-128 Myr [Mantovani et al., 1993], with older ages in the north and younger ages in the southeast corner of the present outcrop.

Mesozoic flood basalts equivalent to the Serra Geral basalts are found in Southwest Africa. These Etendeka Basalts were estimated to have erupted 135±5 Myr based on compilation of K/Ar dates [Rampino and Stothers, 1988], but the ages have a large range as a result of alteration, and in some cases Ar-retention [Milner et al., 1995]. The five existing ^{40}Ar/^{39}Ar age determinations on Etendeka basalts and the related Damaraland igneous complexes gave a range between 124 to 132 Myr, and recently, Milner et al. (1995), performed new Rb-Sr and ^{40}Ar/^{39}Ar age determinations on rocks from the SW Africa. Three new Rb-Sr ages on nepheline syenite and quartz latite intrusions in Damaraland give 126.8±1.3, 126.6±7.3*, and 129.1±3.6 Myr (2σ errors), whereas ^{40}Ar/^{39}Ar age determinations from these igneous complexes gave plateau ages of 135.0±0.7, 125.1±0.6*, and 137.0±0.7 Myr, and isochron ages (on the same samples) of 140.7±1.0, 125.8±1.4*, and 137.2±0.8 Myr (all 1σ errors) (the asterisk indicates age determinations on the same sample from the Okorusu complex). Milner et al. (1995) estimate that the voluminous Etendeka flood basalts were erupted mainly between 135 and 132 Myr. The oldest seafloor anomaly that can be recognized off the Namibia coast is M4, which is dated at ~130 Myr.

Antarctic (Ferrar) Basalts. Compilation of 18 ^{40}Ar/^{39}Ar ages for the Antarctic Basalts (the Ferrar Group, including the Kirkpatrick Basalt and Ferrar Dolerite) [Kyle et al., 1980; Fleck et al., 1977; Heiman et al., 1994] produces an age distribution with a mean of 173.6 Myr, a median at 176.3 Myr and a well-defined peak age at 176.6 Myr (Fig. 1i). We used only one date from Fleck et al. (1977), as this is their only ^{40}Ar/^{39}Ar age determination that yielded an acceptable plateau. The six age determinations taken from Kyle et al. (1980) average 175.9 Myr. Included in our compilation are 11 high-quality ^{40}Ar/^{39}Ar age determinations on feldspar separates from the Kirkpatrick Basalt that by themselves gave a tight mean age of 176.6 ± 1.8 Myr (1σ), as recently reported by

Heimann et al. (1994). Basaltic rocks with similar K/Ar ages occur in Tasmania.

Karoo Basalts. Fitch and Miller (1984) published fifteen ^{40}Ar/^{39}Ar age determinations of igneous rocks from the Karoo Flood Basalt Province of South Africa. However, these determinations generally gave poor plateaus, and suffered from a number of problems including Ar loss, excess Ar, and contamination with atmospheric Ar. Interpretation of the age spectra gave a wide range of estimated ages from ~204 Myr to ~143 Myr, mirroring a similarly problematic large range in published K/Ar determinations for the Karoo Basalts [Fitch and Miller, 1984; see Rampino and Stothers, 1988]. These ^{40}Ar/^{39}Ar age determinations did not produce a coherent histogram, and the spread of ages may reflect problems of reheating during subsequent geological activity and/or alteration of the basalts. Recently, a report of seven new ^{40}Ar/^{39}Ar age determinations from top to bottom of a 1,500 m section of Karoo basalts from Lesotho gives a preliminary age of 182±2 Myr (2σ?) [Hooper et al., 1993].

Our compilation contains four high-quality ^{40}Ar/^{39}Ar plateau ages for basaltic dikes in the Falkland Islands, which are most likely related to the pre-breakup Karoo activity in Africa [Musset and Taylor, 1994]. The distribution yields a peak age of ~190 Myr (Fig. 1j), which agrees with the major peak in Karoo volcanism at ~193±5 Myr as suggested by results of K/Ar dating and paleomagnetic analyses [see Fitch and Miller, 1984; Rampino and Stothers, 1988].

Eastern North American (Newark) Basalts. The Newark Basalts are part of a large East Coast Margin Igneous Province [Holbrook and Kelemen, 1993]. Dating of the Newark Basalts and related intrusions by K/Ar and ^{40}Ar/^{39}Ar methods has been problematic. Our compilation of ^{40}Ar/^{39}Ar age determinations for the Eastern North American Basalt Group contains 36 dates (two of which lacked errors and were not included in the histogram) [Dallmeyer, 1975; Sutter, 1985; Sutter and Smith, 1975; Dunning and Hodych, 1990] giving a mean of 190.7 Myr, a median of 199.4 Myr and a peak age of 201 Myr (Fig. 1k).

The age determinations have a wide range of about 30 Myr, from 171.2±2 to 202.6±0.5 Myr (1σ). K/Ar age determinations give a similar large range of apparent ages [Rampino and Stothers, 1988; Gohn et al., 1978], and the range in the dates may be the result of argon loss, or slow cooling of the diabase intrusions, and hence the mean age may be an underestimate. Sutter (1988) presented evidence for an episode of hydrothermal activity at ~175 Myr, based on argon-closure ages for potassium feldspars from granophyric rocks associated with diabase in the Newark and Culpepper Basins, and this has recently been confirmed by paleomagnetic studies showing growth of secondary magnetite associated with the hydrothermal event [Kodama and Mowery, 1994].

In this case of somewhat problematic ^{40}Ar/^{39}Ar age determinations on the basalts, the best age determination of the Newark igneous rocks may be the ^{40}Ar/^{39}Ar and U/Pb ages from the Palisades and Gettysburg sills (201.0±1.0 Myr, 1σ), and U/Pb zircon and baddeleyite ages from the North Mountain Basalt, Fundy Basin (202±1Myr, 1σ), [Dunning & Hodych, 1990; Hodych and Dunning, 1992; Fowell and Olsen, 1993]. This agrees with stratigraphic evidence of the basalt flows just above the Triassic/Jurassic boundary [Olsen et al., 1990; Fowell and Traverse, 1995], recently estimated to be about 205.7±4 Myr (2σ) [Gradstein et al., 1995]. Study of the cyclostratigraphy of the enclosing and interbedded sedimentary strata of the Newark Supergroup suggests that the duration of the extrusive event was only about 550,000 years [Olsen et al., 1990].

Ten additional ^{40}Ar/^{39}Ar age determinations are available [Sutter and Smith, 1979], ranging from 180.4±6.9 to 194.2±5.3 Myr (2σ), with a mean of 184.3 Myr, that have generally poor plateaus, and large uncertainties when they are corrected to fit newer decay constants [Hodych & Hayatsu, 1988]. Seidemann et al. (1984) gave a series of ^{40}Ar/^{39}Ar age determinations ranging from 187±10 to 202±14 Myr, but these were not used here because of generally poor plateaus and the large associated errors.

On the eastern side of the Atlantic, twenty ^{40}Ar/^{39}Ar age determinations of basalts from Iberia and North Africa [Sebai et al., 1991], which may be related to the same volcanic episode that produced the Eastern North America Basalts, range from 211.4±6.8 to 175.2±0.3 Myr, and give a mean age of 196.2 Myr, but these age determinations may have the same problems as those mentioned for the Newark Basalts, and also seem to show evidence for a tectonic/hydrothermal degassing event at about 175 Myr. The data from Iberia and Morocco both show peaks at ~202 and ~197 Myr, with an additional peak at 185 Myr found only in the Iberian data, and a peak at 175 Myr found only in the Moroccan data. Dates from Algeria and Mali displayed peaks at 198 and 202 Myr respectively.

Histograms were also constructed based on the type of date obtained (but are not included in Fig. 1). Single well-defined peaks were produced by ^{40}Ar/^{39}Ar plateau (201 Myr) and disturbed-spectrum (198 Myr) ages. By contrast, the total ages displayed a wide scatter, with peaks at 175, 180, ~187-190 and 195 Myr. Our preferred age distribution for the Central Atlantic Basalts (Fig. 1l) contains 10 dates, and was constructed using the plateau ages from Sebai et al. (1991) and Feichtner et al. (1992). The distribution yields a peak age of 201.4 Myr, and median of 201 Myr.

Siberian Basalts. Our compilation contains eight age determinations of the Siberian Basalts (Fig. 1k) [Renne and Basu, 1991; Dalrymple et al., 1991; Baksi and Farrar, 1991; Campbell et al., 1992]. Renne and Basu (1991) obtained an age of 248.4±2.4 Myr (2σ) for the Siberian Basalts by ^{40}Ar/^{39}Ar techniques. Baksi and Farrar (1991) had earlier reported considerably younger ^{40}Ar/^{39}Ar dates of 238.4±14 to 229.9±2.3 Myr (2σ) for the bottom and top of the Siberian basalt pile, but subsequent restudy of these rocks gave ages of 243 to 244±1.2 Myr (2σ). Dalrymple et al. (1991) obtained ages of 243.5±1.8 and 244.9±1.8 Myr (2σ) on the same samples, and an age of 249±1.6 Myr (2σ) for biotite from a mineralized vein in the Noril'sk I intrusion, that was confirmed by a SHRIMP U-Pb date of 248±4 Myr (2σ) for a zircon from a eutaxitic leucogabbro in the Noril'sk I [Campbell et al., 1992]. These agree, to within laboratory errors, with the age determinations of Renne and Basu (1991). Campbell et al. (1992) determined an age for the Siberian Basalts of 248±2 Myr (2σ).

A recent calibration of ^{40}Ar/^{39}Ar dating standards to the astronomical timescale suggests a revised age of 249.6±1.5 Myr (2σ) [Renne et al., 1994]. The basalts apparently straddle the Permian/Triassic boundary, recently dated by the U/Pb method at 251.2±3.4 Myr (2σ) [see Gradstein et al., 1995]. A recent study by Renne et al. (1995) reveals that the Siberian Basalts appear synchronous with the Permian/Triassic extinction within the limits of detection. We have adopted his age of 250 Myr as the preferred age of the basalt.

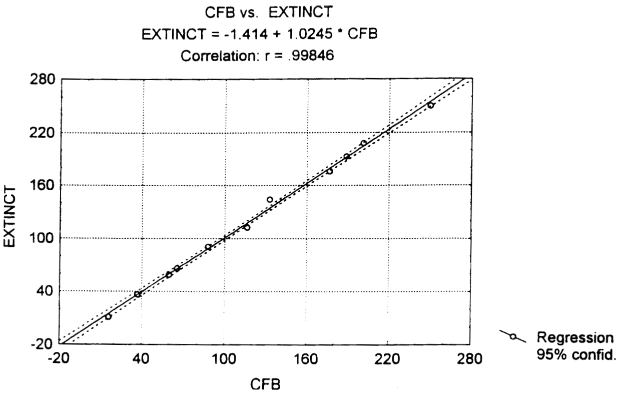

Figure 2. Correlation diagram for flood basalts and mass extinctions.

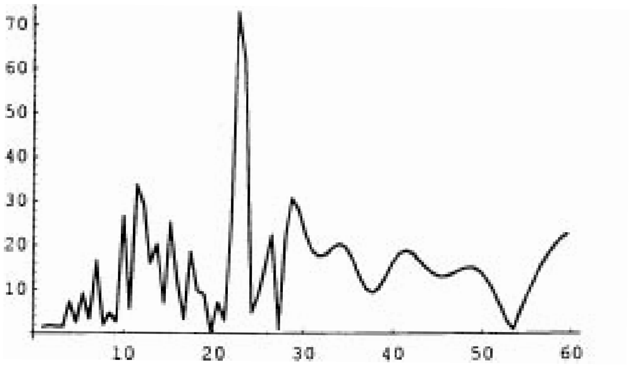

Figure 3. Periodogram of flood basalt ages.

Oceanic Flood Basalts. Recent ^{40}Ar/^{39}Ar age determinations of the oceanic tholeiitic basalts of the Ontong-Java Plateau (Fig. 1g) have produced 10 dates [Mahoney et al., 1993] that range from 119.9±2.6 to 124.7±2.2 Myr with a mean of 122.3 Myr (2σ). Four additional, much younger age determinations, which range from 82.5±3.1 to 92.6±1.4 Myr (2σ), and have a mean of 87 Myr, possibly represent a more recent period of activity, or the overriding of a hotspot by the plateau [Mahoney et al., 1993]. Basalts from the Manihiki Plateau yielded a similar weighted ^{40}Ar/^{39}Ar plateau age of 123±1.5 Myr (2σ) [Mahoney et al., 1993].

A somewhat older oceanic plateau, the Shatsky Rise in the Northwest Pacific is bounded on the south by magnetic anomaly M-21 (~150 Myr), and M12 (~138 Myr) brackets the northern high. However, these ages must be considered uncertain by at least ±5 Myr. Coring of earliest Cretaceous sediments in the northern region implies a latest Jurassic basement age by extrapolation [Sager and Han, 1993].

The Caribbean Cretaceous Basalt Province [Bence et al., 1975] may represent the tectonized remains of an oceanic plateau that became trapped between the North American and South American Plates. The oceanic crust beneath the Caribbean Sea is anomalously thick, as would be expected for the remnants of a large oceanic plateau, and recent ^{40}Ar/^{39}Ar age determinations of the basalts give ages of ~88 to 89 Myr [Duncan et al., 1994].

Discussion

Correlation of Flood Basalts and Mass Extinctions. A number of studies have suggested that flood basalt eruptions and mass extinctions may be related [MacLean, 1985; Courtillot, 1990]. Rampino and Stothers (1988) found a good correlation between the estimated initiation times of continental flood basalts and the estimated times of mass extinctions of life as determined by Sepkoski (1986). Stothers (1993) subsequently calculated the confidence level of the correlation between an updated list of flood basalt eruptions and mass extinctions, by an objective direct method, to be at the 96 to 99% level.

Table 1 shows the revised initiation dates of the continental flood basalts based on the data compiled here compared with the estimated ages of mass extinction events on the DNAG timescale (after Rampino and Stothers, 1988). On a qualitative level, there is clear evidence for correlation.

Two methods were used to quantitatively assess the proposed correlation. Initially, standard linear regression techniques were applied to a correlation diagram (Fig. 2) for extinctions and flood basalts. Pearson's correlation coefficient was calculated to be >.99. Any two increasing vectors will show a strong correlation, so this cannot be taken by itself as compelling evidence for correlation. To overcome these problems, the cross correlation method developed by Stothers (1993) was also applied to the data set. This method is more robust than Pearson's r when applied to time series. The rms difference between nearest neighbors in the two series is calculated and used as a correlation metric. A possible uniform phase shift is considered, and the most likely lag time is found. We find that the correlation of the two data sets is at the 95-97% confidence level with no lag time between the events. It is highly significant, and somewhat surprising, that a strong correlation is found using the newest data sets for both flood basalts and extinctions.

One continental flood basalt that seems not to correspond to a significant mass extinction event as listed by Sepkoski (1989), however, is the North Atlantic Basalt Province, although our estimated age of ~60.5 Myr, and stratigraphic and paleomagnetic evidence, suggests that the basalts were erupted in the Late Paleocene and possibly across the Paleocene/Eocene boundary. The Paleocene/Eocene Epoch boundary interval can be placed in Magnetic Chron C24R (~57.8±2 Myr), and is marked by major environmental changes, a negative δ^{13}C shift in benthic foraminifera, and extinctions among diverse groups such as benthic foraminifera and land mammals [Rea et al., 1990; Thomas, 1992; Molina et al., 1994].

Time Series Analyses of Flood Basalt Ages. The mean interval between continental flood basalt events is between 20 and 23.2 Myr, depending on whether one considers the closely spaced (~5 Myr) North Atlantic and Deccan eruptions as separate events, or two phases of a single "global CFB episode." The flood basalt episodes are clearly not regularly periodic, but they could represent a mixture of periodic and random components. Previous time series analyses of the dates of flood basalt eruptions produced evidence for a possible periodic component ranging from ~23 to 30 Myr, depending upon the specific initiation dates used and inclusion or exclusion of certain flood basalt provinces [Rampino and Stothers, 1988; Stothers and Rampino, 1990; Rampino and Caldeira, 1993].

Using the revised dates given in Table 1 as delta functions, we computed the Fourier transform of the auto-covariance function of the data set, utilizing a standard Tukey window with a bandwidth of 4.5 Myr [Jenkyns and Watts, 1968] (Fig. 3). The highest peak in the Fourier power spectrum occurs at 22.5 Myr, but tests of statistical significance, with analysis of 1,000 pseudo-time series composed of the same number of events as the flood basalt time series over the same interval of time, revealed that the peak had a relatively low significance level. The low significance level, however, could easily be the result of the relatively small number (9) of independent episodes. Several studies have shown that this range of periodicity is not unexpected in a data set composed of both periodic and random events, and that the periodicities overlap with those found in the mass extinctions when different methods of dating are taken into account (e.g., Fogg, 1988; Trefil and Raup, 1986). These analyses, however, are also plagued by small number statistics, and other studies have reported no significant periodicities in various sets of dated craters [Grieve, 1991].

Flood Basalts, Climatic Change, and Mass Extinctions. The correlation between flood basalt episodes and mass extinctions, if real, implicates volcanism as a factor in extinctions. Flood basalts have been related to the inception of mantle plume activity, and thus may represent one facet of a host of geological factors (e.g., changes in seafloor spreading rates, rifting events, increased tectonism and volcanism, and sea-level variations) that may be associated with mantle plume activity [Larson, 1990]. Flood basalt eruptions have been suggested as a primary or contributing cause of mass extinctions [e.g., McLean, 1985; Courtillot et al., 1986; Courtillot, 1990; Glen, 1994; Courtillot, 1995]. Possible mechanisms for such a causal link have been debated at length [see Courtillot et al., 1995].

Conclusions. Our new compilation of published ^{40}Ar/^{39}Ar age determinations of Mesozoic/Cenozoic flood basalts, presented as Gaussian probability distributions, allows improved estimates of the initiation time and duration of the major flood basalt provinces. The age distributions of twelve individual flood basalt episodes from the last 250 Myr suggest that in most cases the eruption of the bulk of the voluminous basalt flows took place in <1 Myr. Time series analysis reveals equivocal evidence or a quasi-periodicity of 23 Myr.

The estimated initiation times of these continental flood basalt eruptions are found to correlate with the independently determined ages of mass extinctions of life at a confidence level >97% (within the estimated errors in ages of eruptions and extinctions). Projected environmental and climatic effects of these mega-eruptions may be severe, and flood basalt events may have played a large role in the extinctions.

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