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MASS EXTINCTION

The eruptive tempo of Deccan volcanism in relation to the Cretaceous-Paleogene boundary

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Late Cretaceous records of environmental change suggest that Deccan Traps (DT) volcanism contributed to the Cretaceous-Paleogene boundary (KPB) ecosystem crisis. However, testing this hypothesis requires identification of the KPB in the DT. We constrain the location of the KPB with high-precision argon-40/argon-39 data to be coincident with changes in the magmatic plumbing system. We also found that the DT did not erupt in three discrete large pulses and that >90% of DT volume erupted in <1 million years, with ~75% emplaced post-KPB. Late Cretaceous records of climate change coincide temporally with the eruption of the smallest DT phases, suggesting that either the release of climate-modifying gases is not directly related to eruptive volume or DT volcanism was not the source of Late Cretaceous climate change.

The mass extinction at the Cretaceous-Paleogene boundary (KPB) fundamentally reshaped Earth's biosphere, ending the >150-million-year Age of the Dinosaurs and paving the way for the rise and dominance of mammalian fauna. Understanding this event is important for several reasons, including its implications for mammalian evolution and the effects of abrupt climate change. Hypotheses regarding the cause of the mass extinction center around two potential triggers, invoking one or both: voluminous flood basalt volcanism (totaling >10^6 km^3 of magma) from the Deccan Traps (DT) (in modern-day India) and the large bolide impact recorded by the Chicxulub crater. The impact hypothesis is supported by the Chicxulub crater (which coincides in age with the main extinction event) (*1*) and by a global KPB impact ejecta layer (consisting of an iridium anomaly, spherules, shocked minerals, and Ni spinels) (*2*–*4*), in addition to evidence of abrupt extinction recorded by marine microfossils and terrestrial pollen and spores [e.g., (*5*, *6*)]. Support for the Deccan hypothesis includes geochronologic evidence that much of the DT erupted around the KPB within a time span of ~1 million years (Ma) (dominantly within chron C29r) (*7*–*10*), and DT volcanism roughly coincides with Late Cretaceous records of climate change, in addition to records of ecological stress observed in some terrestrial and marine faunas (*11*–*15*). Furthermore, a temporal correlation between other flood basalt eruptions and major ecological crises in Earth's history suggests the potential for the DT to have caused the mass extinction alone (*16*). Additional hypotheses suggest a connection between the two mechanisms. Richards *et al.* (*17*) hypothesized that major transitions in lava flow morphology, flow-field volume, and feeder-dike orientation observed within the DT stratigraphy were a result of a reorganization of the magmatic plumbing system triggered by seismic energy from the Chicxulub impact (*7*, *17*), overall enhancing volcanism in the DT around the time of the KPB.

Central to the hypothesis that the DT played a contributing role in the mass extinction is the assumption that large amounts of climate-modifying gases (CO_2, CH_4, and SO_2) were released by the Deccan before the KPB. Earlier geochronological studies (*10*, *18*, *19*) suggested that the DT erupted in three phases, with ~80% of the extrusive volume erupting in phase 2, a short pulse starting ~400,000 years before the KPB and ending at the boundary. Phase 2 is often cited as the source of Late Cretaceous environmental change (*12*, *14*, *20*–*22*). With the proposed location of the KPB as suggested from the transitions described above, attributed to the effects of the Chicxulub impact (*7*, *17*), it has also been hypothesized that >75% of the volume of the DT erupted post-KPB. Current high-precision geochronology [U-Pb (*8*) and ^{40}Ar/^{39}Ar (*7*)] cannot adequately test among these hypotheses because of sampling gaps that fail to pinpoint the KPB within the Deccan lava stratigraphy. To better understand the role of DT volcanism in end-Cretaceous environmental change and mass extinction, here we report high-resolution ^{40}Ar/^{39}Ar plagioclase ages from the DT that locate the KPB and better refine the timing and tempo of eruptive fluxes.

We measured 19 high-precision ^{40}Ar/^{39}Ar ages for the DT that complement the previous geochronology to create a higher-resolution temporal framework for DT volcanism. We collected samples for geochronological analysis from the Western Ghats region of the DT, the most relevant region for understanding DT-induced climate change, as the record of the most voluminous eruptive phase of the DT occurs here (Fig. 1). The total lava stratigraphy is called the Deccan Group, which is divided into formations within the larger Kalsubai, Lonavala, and Wai subgroups (in ascending order) (Fig. 1). These formational and subgroup boundaries arise from geochemical and volcanological properties (*23*). Each formation comprises multiple eruptive units. In total, we sampled each subgroup and all but two formations within these subgroups, including the stratigraphically highest and lowest dated samples from the Western Ghats. Our samples came from multiple sections. We focused sampling near the Lonavala–Wai Subgroup transition, the hypothesized location of the KPB because of changes in lava flow morphology, flow-field volumes, and geochemistry ascribed to effects of the Chicxulub impact (*7*, *17*). We collected samples to fill in the sampling gaps from Renne *et al.* (*7*) and Schoene *et al.* (*8*), which allows testing and improvement of their geochronological models.

The ^{40}Ar/^{39}Ar method dates the eruption of lavas without the need for assumptions about pre-eruptive residence time or provenance, as are required for U-Pb zircon dates. We analyzed samples in detailed (11- to 21-step) step-heating experiments with multigrain aliquots of plagioclase separates (fig. S1). To achieve high precision, we analyzed three to eight aliquots per sample (fig. S1), densely bracketed by standards during irradiation in order to precisely determine the neutron fluence (*19*). We report here the weighted mean plateau ages for each of our samples (table S1) [errors are reported at an SEM of 1-σ, with *X* versus *Y* indicating analytic versus systematic uncertainty, respectively, per (*24*)].

When we combined our data with previously published high-precision dates (*7*), we found that the DT lavas erupted quasi-continuously for 991,000 years (see Fig. 2), from ~66.413 Ma ago [the date for Jawhar Formation (Fm.) sample KAS15-3] to ~65.422 Ma ago (the date for upper Mahabaleshwar Fm. sample PAN15-3). This time interval represents a total estimated volume of ~560,000 km^3 [on the basis of volume estimates presented in (*17*), where estimates are weighted by areal extent], including ~93% of the total estimated volume of the DT. By using our composite stratigraphic section, we determined from our data that ~85% of the Kalsubai Subgroup erupted in a period of 242,000 ± 101,000 years, that ~95% of the Lonavala Subgroup erupted in 46,000 ± 129,000 years, and that ~95% of the Wai Subgroup erupted in a period of 690,000 ± 185,000 years.

From our age estimates for the Jawhar Fm., we found no evidence for older eruptions [the basis for "phase 1" and the proposed Latifwadi Fm. (*10*, *18*, *19*)]. Additionally, with our new data, we

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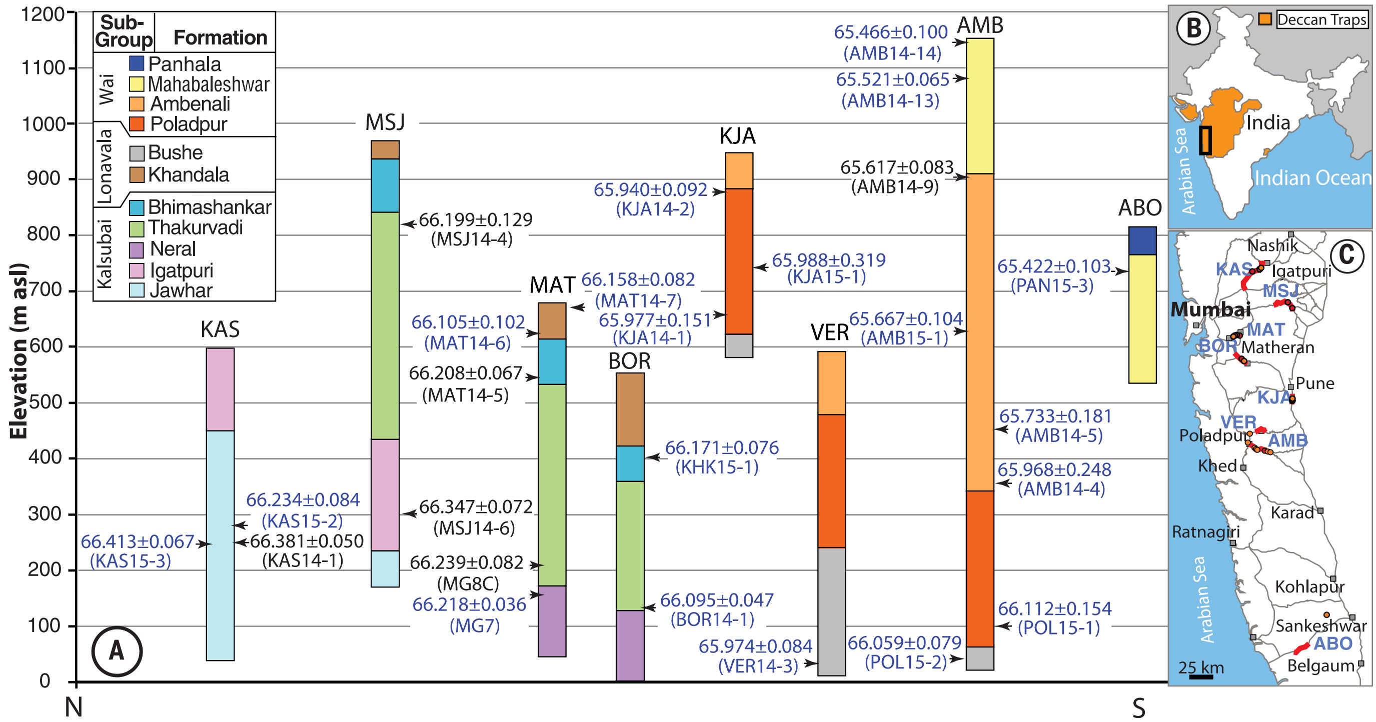

Fig. 1. Stratigraphy and location map. (**A**) Dated horizons within stratigraphic sections. Ages reported in millions of years are shown with 1-σ uncertainties (SEM). Ages shown in blue are new ages reported in this study, and ages in black were reported in (*7*). Sample names for dated horizons are given in parentheses. Dates for MG7 and BOR14-1 are the weighted mean ages combined with results presented in (*7*). Stratigraphy for sections KAS (Shahapur-Igatpuri), MAT (Matheran-Neral), BOR (Khopoli-Khandala), and AMB (Mahabaleshwar-Poladpur) was adapted from (*9*, *10*). Stratigraphy for the ABO (Amboli Ghat) section was adapted from (*32*). Stratigraphy for the MSJ (Malshej Ghat) section was acquired in (*7*). Stratigraphic information for the KJA (Katraj Ghat) and VER (Varandha Ghat) sections was acquired in this study. asl, above sea level. (**B**) Location map of samples collected in this study. (**C**) Sampled traverses within the Western Ghats region. Orange dots indicate samples presented in this study, and red dots indicate samples presented in (*7*).

have further confirmed that the KPB is not located at the contact between the Mahabaleshwar and Ambenali formations but is lower in the stratigraphy and that no obvious, long hiatus in eruption occurred near the KPB. By contrast, we find an enhanced period of eruption around the time of the KPB, demonstrated by rapid emplacement of the Poladpur Fm. We thus conclude that the persistent concept of three discrete phases of Deccan eruptions in the manner defined by Chenet *et al.* (*10*, *18*) in the Western Ghats is an artifact of limited and lower-precision geochronology and hence should be not be used for interpreting paleoenvironmental-proxy records (*19*).

We place the KPB horizon (dated at 66.052 ± 0.008/0.043 Ma via the $^{40}Ar/^{39}Ar$ technique on a volcanic ash located 1 cm above the Ir anomaly in eastern Montana, USA) (*25*) within or near the top of the Lonavala or the basal Wai Subgroup, roughly coincident with the observed transitions that are suggested to reflect a fundamental change in the DT magmatic plumbing system. Within the uncertainty of our data, ages from the Bushe Fm. through the lower Ambenali Fm. overlap within the uncertainty bounds of the KPB. To test the hypothesis that the KPB coincided with the transition between the Bushe and Poladpur formations at the top of the Lonavala Subgroup (*17*), we employed the Bayesian age model "Bacon" (*26*). Because of uncertainties in volume estimates and possibly diachronous formation contacts between sections, the most secure application of such models is to data from a continuous stratigraphic section. Accordingly, we modeled our data from the Ambenali Ghat section, our sole section containing the Bushe-Poladpur contact in a larger stratigraphic context. In this section, the contact is bracketed to within 50 m by one date from the Poladpur Fm. and one from the Bushe Fm. We found an interpolated age of 66.03 ± 0.04 Ma (68% confidence) for the Bushe-Poladpur transition (Fig. 3), which is indistinguishable from the 66.052 ± 0.008 Ma $^{40}Ar/^{39}Ar$ age of the KPB (*25*). The results of our age model indicate that the transition from the Bushe Fm. to the Poladpur Fm. at Ambenali Ghat occurred between 60,000 years before and 20,000 years after the KPB. We cannot exclude the possibility that the KPB occurs within the Bushe or the lower half of the Poladpur Fm., but the most probable placement according to our model is ~25 m below the contact between the two. With these results, we cannot reject the hypothesis that the major transitions observed within the Deccan stratigraphy near the Bushe-Poladpur boundary are due to changes in the magmatic system caused by the seismic energy from the Chicxulub impact.

By using the above-described placement for the KPB, we determined a mean magma extrusion rate of 0.4 ± 0.1 km^3/year, representing 124,000 km^3 of lava, for units erupted before the KPB (comprising the Kalsubai and Lonavala subgroups) and a mean extrusion rate of 0.6 ± 0.2 km^3/year, representing 435,000 km^3 of lava, for units emplaced after the KPB (comprising the Wai Subgroup) (Fig. 2). These results suggest that the mean extrusion rate may have increased after the KPB. Furthermore, using this placement of the KPB within the Deccan stratigraphy indicates that >75% of the DT volume erupted within ~650,000 years around or after the KPB. Using instead our upper bound of the placement of the KPB near the top of the Poladpur Fm. suggests that >50% of the erupted volume was emplaced after the KPB. Both of these results are in stark contrast to previously proposed eruption time scales, which had ~80% of the Deccan volume emplaced before the KPB (*10*).

Our results require a fundamental reassessment of the role of the DT in the KPB mass extinction if the release of climate-modifying magmatic gases (mainly CO_2 and SO_2) was synchronous with the

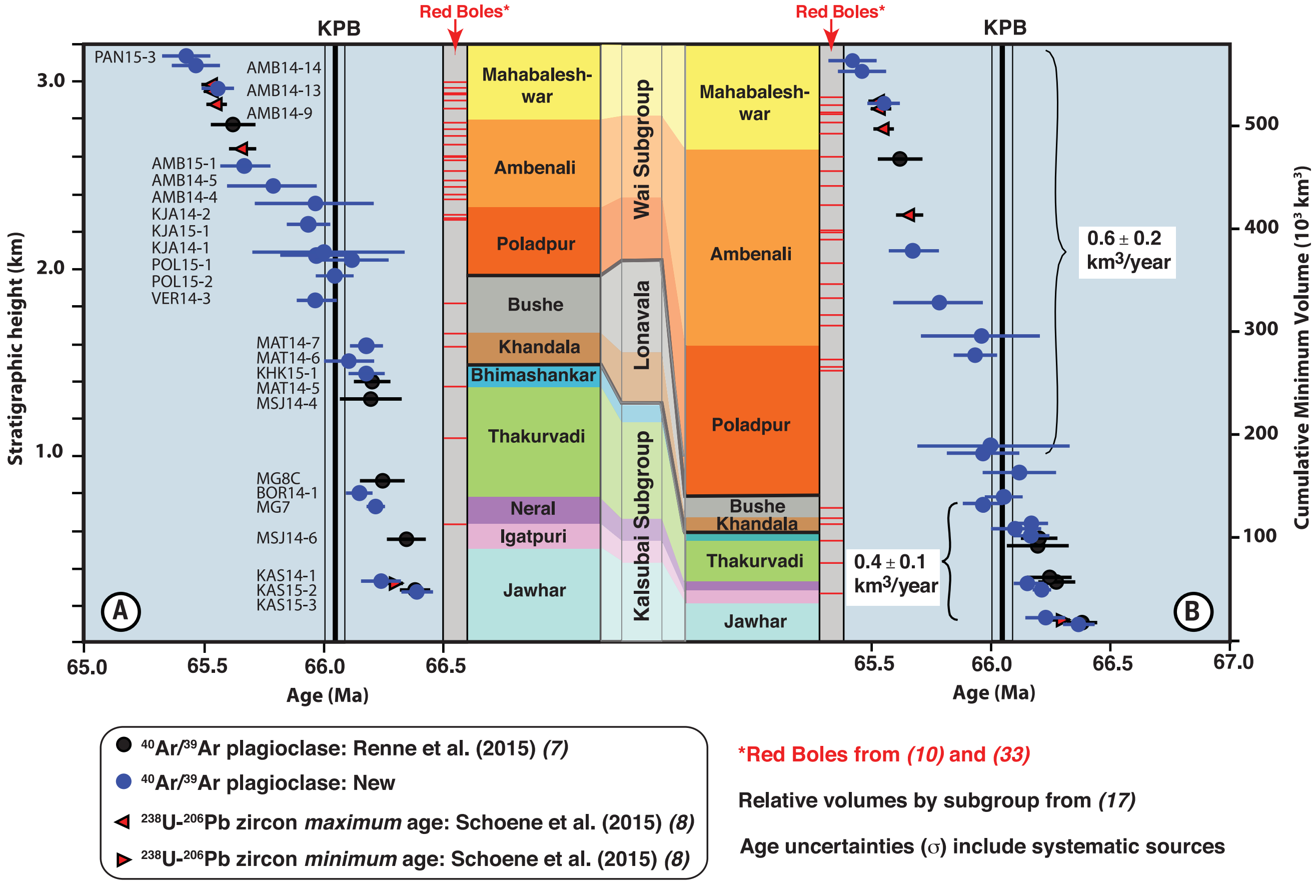

Fig. 2. Stratigraphic summary and eruptive history. Composite stratigraphic thickness (**A**) and cumulative volume (**B**) versus age for chemical formations within the DT volcanic group from the Western Ghats. All ages are plotted with 1-σ uncertainties (including systematic sources).

climax of erupted lava volume, as is commonly assumed. Because the most voluminous Wai Subgroup lava flows were emplaced around or after the KPB, the largest climatic impact, on the basis of the above-mentioned assumption, should be expected at this time as well, either just before or in the 600,000 years after the KPB. Contrary to this expectation, proxy records show no evidence for major climate change in the million years post-KPB besides a short-lived (months to millennia) pulse of cooling (2° to 4°C) immediately after the KPB and a ~100,000-year record of warming (~5°C) postextinction, which have both been attributed to the Chicxulub impact (Fig. 4), in addition to a general similarity between the duration of post-KPB volcanism and marine and terrestrial biotic recovery (~1 Ma) (*27, 28*). Instead, what is seen is that the largest climatic changes occurred before the KPB, with a ~2.5° to 5°C warming event around 150,000 to 450,000 years before the KPB, followed by a ~5°C cooling event leading up to the KPB, during the eruption of the smallest-volume phases of the DT (*11, 14, 15*). It follows either that the DT was not the cause of Late Cretaceous climate change and did not play a role in the mass extinction or that the release of climate-modifying gases is not directly related to erupted lava volume, as previously assumed.

Over the past few decades, increased monitoring and measurements at present-day volcanic systems have shown that a substantial quantity of magmatic volatiles can be degassed from the magma reservoir at a shallow crustal depth without any corresponding lava flow forming eruptions [e.g., (*29*) and references therein]. These volatiles are introduced passively into the atmosphere through preexisting faults and surface hydrological systems. The release of volatiles because of magmatic heating of crustal materials such as coal has been inferred as a source for CO_2 related to other flood basalts [e.g., (*30*)], which may be decoupled from eruptive activity. Whereas passive degassing of CO_2 would have a global warming impact similar to that of CO_2 injected during an eruption, SO_2 (which converts to sulfate aerosols in the atmosphere) needs to make it into the stratosphere in voluminous eruptions and be nearly continually replenished to have a global cooling effect because of sulfur's short residence time in the troposphere.

To reconcile pre-KPB and post-KPB climate signals with our estimated DT eruptive fluxes, we propose the following conceptual model (Fig. 4). The initiation of the Deccan mantle plume and the initial emplacement of magma in the lithosphere and cold, upper crust led to degassing of a large amount of magmatic volatiles (especially CO_2) before the surface eruptions resulting in global warming (*31*). Subsequently, if recurrence times were short enough, the increase in the DT surface eruptive flux approaching the KPB would have led to the persistent injection of sulfur into the atmosphere and a pre-KPB global cooling, or conversely, silicate weathering feedbacks could have drawn down CO_2 from the atmosphere, also resulting in global cooling (*15*). We expect the proposed pre-KPB degassing to be dominated by magmatic volatiles as opposed to carbon released by the metamorphism of sedimentary organic material, as there is no major negative carbon isotope anomaly coinciding with the pre-KPB warming (*15*), in addition to there being no evidence of organic-rich rock in the Deccan basement. This suggests that sources of isotopically light carbon (e.g., biogenic methane or the oxidation of organic matter) were not destabilized and released in substantial quantities during the DT event (*15*). Post-KPB, DT eruptions were marked by larger eruptive events followed potentially by longer hiatuses between eruptions (*7*). These longer recurrence intervals obviated the buildup of sulfate aerosols and allowed for CO_2 drawdown through silicate weathering and organic carbon burial, leading to lower levels of accumulated atmospheric CO_2 partial pressure. In addition to longer recurrence intervals, early-stage passive degassing may have reduced the volatile content in magmas erupted after the KPB, which may have been pushed to eruption by processes related to the Chicxulub impact.

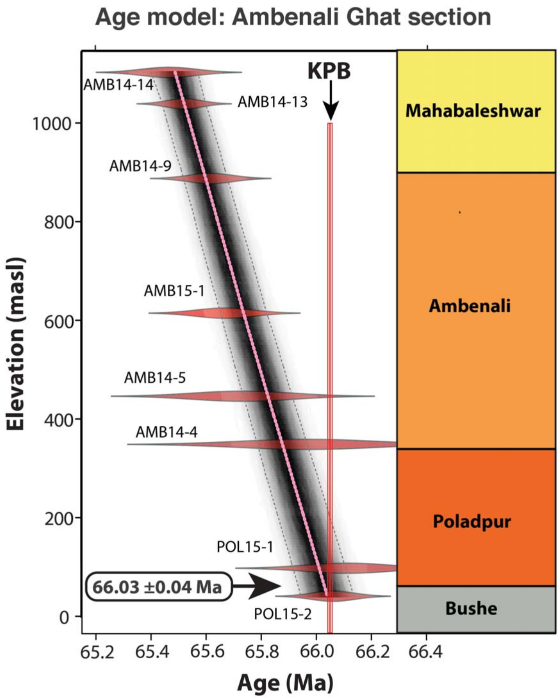

Fig. 3. Bayesian age model for the Ambenali Ghat section. Results indicate an interpolated age of 66.03 ± 0.04 Ma (68% confidence) for the Bushe-Poladpur transition, which is indistinguishable from the 66.052 ± 0.008 Ma $^{40}Ar/^{39}Ar$ age of the KPB (*25*). The Bayesian age model Bacon (*26*) was used (*19*). Age uncertainties (red ellipses) are shown at 2-σ and exclude external sources. masl, meters above sea level.

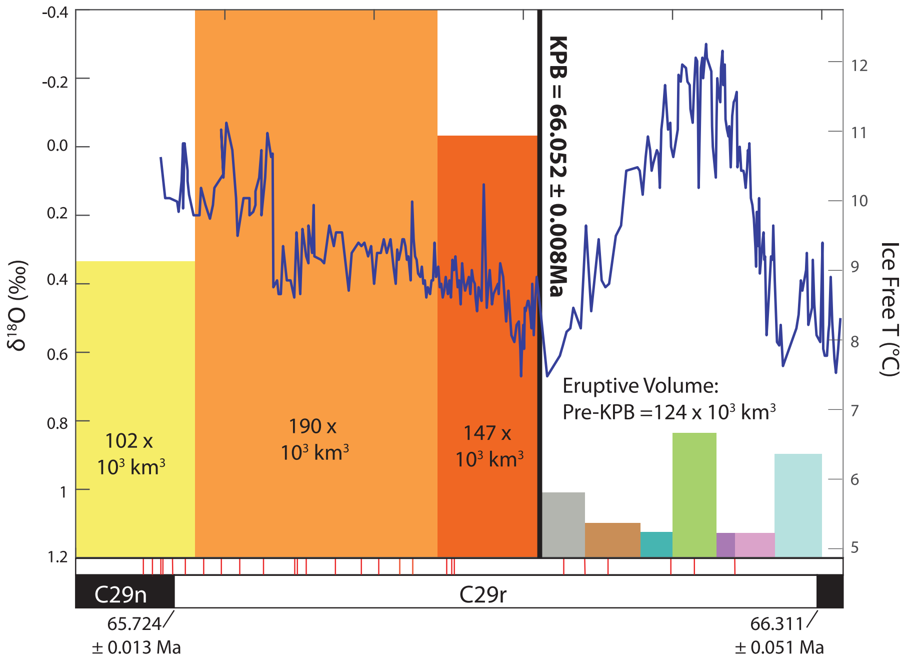

Fig. 4. Eruptive flux and climatic changes. Correlation of Deccan eruptive fluxes to benthic $\delta^{18}O$ data from Ocean Drilling Program site 1262 (blue line) [published in (*15*)]. Colored blocks represent eruptive fluxes, where color indicates the formation per Fig. 2; horizontal length indicates the approximate duration; and height is scaled by eruptive volume as calculated in (*17*). Red lines mark the known locations of red boles taken from (*9*, *10*, *33*). Magnetozones for the oxygen isotope data (Deccan) are from (*9*, *10*, *33*, *34*). Ages shown for the KPB, C29r/C29n, and C30n/C29r reversals are $^{40}Ar/^{39}Ar$ ages from (*25*). *T*, temperature.

Although the above-described model helps to reconcile our calculated DT eruptive fluxes with observed climate changes around the KPB, to truly understand the specific role Deccan volcanism played in the KPB mass extinction, a better understanding of its volatile release is required. In particular, better estimates of the amount and specific species of gas released and an improved understanding of the relationships among lava extrusion, volatile release both during eruptions and passively, and climatic effects of large igneous provinces need to be obtained.

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C.J.S. collected samples, processed and analyzed samples, interpreted results, and wrote and edited the manuscript; P.R.R. collected samples, processed and analyzed samples, and participated in interpretation and the writing and editing of the manuscript; L.V., S.S., K.P., and T.M. collected samples and participated in interpretation and the writing and editing of the manuscript. **Competing interests:** None declared. **Data and materials availability:** All data are available in the supplementary materials.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/363/6429/866/suppl/DC1
Materials and Methods
Supplementary Text
Fig. S1
Tables S1 and S2
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