40Ar/39Ar ages of alkaline and tholeiitic rocks from the northern Deccan Traps: implications for magmatic processes and the K–Pg boundary

Laura Parisio1*, Fred Jourdan2, Andrea Marzoli1,3, Leone Melluso4, Sam F. Sethna5 & Giuliano Bellieni1

1 Dipartimento di Geoscienze, Università degli Studi di Padova, Via Gradenigo 6, 35131 Padova, Italy
2 Western Australian Argon Isotope Facility, JD Centre & Applied Geology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
3 CNR-IGG Padova, Via Gradenigo 6, 35131 Padova, Italy
4 Dipartimento di Scienze della Terra, Ambiente e Risorse, Università di Napoli Federico II, Via Mezzocannone 8, 80134 Napoli, Italy
5 Department of Geology, St. Xavier’s College, Mumbai, 400001, India
*Correspondence: lauraparisio@libero.it

Abstract: The Deccan large igneous province in India was emplaced temporally close to the Cretaceous–Palaeogene (K–Pg) boundary and is formed by tholeiitic flood basalts and less abundant alkaline rocks. Definition of the origin of Deccan magmatism and of its environmental impact relies on precise and accurate geochronological analyses. We present new 40Ar/39Ar ages from the northern sector of the province. In this area, tholeiitic and alkaline rocks were contemporaneously emplaced at 66.60 ± 0.35 to 66.40 ± 2.80 to 64.90 ± 0.80 Ma. The indistinguishable ages for alkaline and tholeiitic magmatism suggest that distinct mantle sources were synchronously active. The new ages are compared with previous ages, which were carefully screened and filtered and then recalculated to be comparable. The entire dataset of geochronological data does not support a time-related migration of the magmatism related to the northward Indian plate movement relative to the Reunion mantle plume. The main phase of magmatism, including the newly dated rocks from the northern Deccan, occurred at the K–Pg boundary. This suggests a causal link between the emplacement of the province and the K–Pg mass extinction.

Supplementary material: Whole-rock and mineral compositions and the complete 40Ar/39Ar dataset are available at https://doi.org/10.6084/m9.figshare.c.2674441.

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The Deccan Traps are one of the large igneous provinces (LIPs) in the world and are located in the northwestern portion of India (Fig. 1a). At present they cover an area of about 0.5 million km2, possibly one-third of the estimated original extent (Mahoney 1988). They consist of thick tholeiitic basalt lava piles that reach a maximum exposed thickness of 1700 m (Mahoney et al. 1982; Watts & Cox 1989). The origin of the Deccan Traps is attributed to the migration of India over the Reunion hotspot with a relative southward migration of the continent (Morgan 1981; Hooper 1990; Mitchell & Widdowson 1991). The Deccan Traps are also characterized by scattered occurrences of alkaline rocks, located mainly in the Saurashtra peninsula and in the Narmada rift zone (Krishnamurty & Cox 1980; Gwalani et al. 1993), with small amounts of alkaline rocks mainly cropping out along the Indian Ocean coast in the surroundings of Mumbai (Melluso et al. 2002; Vanderkluysen et al. 2011). The alkaline rocks are generally thought to have been emplaced during both early and late phases of the tholeiitic activity (Basu et al. 1993; Sheth & Pande 2014) and are significant to define the contribution of variably enriched mantle components in the genesis of Deccan magmatism.

The close temporal relationship with the biotic mass extinction of the Cretaceous–Palaeogene (K–Pg) boundary has led to debate on this LIP being one of its possible causes (Courtillot et al. 1988; Self et al. 2006, 2008; Keller et al. 2008), along with the Chicxulub bolide impact (Yucatan Peninsula; e.g. Alvarez et al. 1980; Smit & Hertogen 1980; Alroy 2008; Schulte et al. 2010a). In this context, alkaline magmatism, although having limited volumetric significance, may be a major source of pollutant gases such as CO2, SO2, Cl and F (see Ray 1998). Therefore, precise and accurate ages of the Deccan magmatism are a crucial tool to better constrain the evolution of the province, in terms of its duration, its time-related migration, the relative timing of tholeiitic v. alkaline magmatism, and its impact on the K–Pg mass extinction.

This work aims to provide new ages for Deccan rocks. In particular, we dated mineral separates from alkaline and tholeiitic samples from the northern portion of the Deccan, in the Narmada rift (Fig. 1). These new data show that alkaline and tholeiitic magmatism in the study area are synchronous at about 66 Ma, and that magmatic activity in this northern portion of the province lasted for at least 1 myr and does not conform to a simple southward migration of the magmatism (i.e. to a migration of the India plate over a fixed mantle plume).

Previous geochronological work

Determination of the age of the Deccan Traps has been the aim of many studies in the last 30 years (e.g. Courtillot et al. 1988, 2000; Duncan & Pyle 1988; Basu et al. 1993; Venkatesan et al. 1993, 1996; Baks 1994, 2014; Hofmann et al. 2000; Sheth et al. 2001; Mahoney et al. 2002; Knight et al. 2003; Pande et al. 2004; Cucciniello et al. 2015; Renne et al. 2015; Schoene et al. 2015; Shrivastava et al. 2015; Sheth & Pande 2014) and are
However, many of the published ages are of poor precision or cannot be mutually compared. This latter problem affects in particular 40Ar/39Ar ages calculated relative to poorly intercalibrated standards or standards that have been demonstrated to be heterogeneous and not suitable for high-precision dating (e.g. MMhb-1, SB-3, LP-6; see Onstott et al. 1991; Spell & McDougall 2003; Jourdan & Renne 2007, and references therein). Data filtering

To compare the 40Ar/39Ar ages obtained so far on Deccan samples, they have been recalculated relative to the age of Fish Canyon sanidine (FCs) of 28.294 ± 0.037 Ma and using the decay constants of Renne et al. (2010) calculated following the approach of Renne et al. (2010). It should be noted that recalculated ages would become about 0.2 myr younger if the age (28.1986 ± 0.038 Ma) for the Fish Canyon sanidine standard recently proposed by Wotzlaw et al. (2013) was considered.

A rigorous screen of the available ages has been undertaken and ages satisfying the following criteria have been considered further: (1) age data need to be calibrated with reliable standards (see Jourdan & Renne 2007); (2) 40Ar/39Ar plateau ages must be defined by at least 70% of the released 39Ar and by at least three consecutive steps yielding the same apparent age within 95% confidence level and a probability of fit (P-value) of at least 0.05 (Baksi 2007; Jourdan et al. 2007); (3) if excess Ar is present, robust 39Ar/40Ar–36Ar/40Ar isochron ages (P > 0.05) that take into account the measured isotopic composition of the trapped argon will be considered instead of the plateau model age, which assumes that the initial trapped argon has an atmospheric composition (Harrison et al. 1985). Ages fulfilling these criteria are listed in Table 1, and all other available age

Fig. 1. (a) Map of northwest–central India showing the extent of the Deccan Traps (light blue area), with the approximate location of the intrusive and alkaline bodies (red stars): (1) Sarni Dandali; (2) Mundwara; (3) alkaline olivine basalts in Kutch; (4) Mount Girnar in the Saurashtra Peninsula; (5) Kadi; (6) Netrang; (7) Phenai Mata; (8) Amba Dongar; (9) Barwaha; (10) Jawhar; (11) Murud. Black circles, sampling localities. The numbers in the boxes are the reliable 40Ar/39Ar ages (in Ma) in the Deccan Traps, with all the uncertainties given at the 2σ level (see Table 1); U/Pb ages from Schoene et al. (2015) are also shown. The new 40Ar/39Ar ages from the Phenai Mata, Pavagadh and Rajpilia areas are shown in bold type.

(b) Simplified geological map of the Phenai Mata area (after Gwalani et al. 1993), showing sampling localities (squares, alkaline samples; circles, tholeiitic samples) and 40Ar/39Ar ages.
Table 1. Previous filtered and recalculated $^{40}$Ar/$^{39}$Ar ages

| Reference (standard) | Sample | Plateau or isochron* age | $^{40}$Ar/$^{39}$Ar intercept | Recalculated age |
|----------------------|--------|--------------------------|-------------------------------|-----------------|
| Basu et al. (1993) (FCs = 27.64 Ma) | #79bt1 | 68.5 ± 0.2 | 293.4 ± 10.3 | 69.6 ± 0.22 |
|                      | #79bt2 | 68.6 ± 0.2 | 69.6 ± 0.22 |
|                      | #51bbl1 | 69.4* ± 1.3 | 70.4 ± 1.3 |
|                      | #C11bt-1 | 68.6 ± 0.2 | 69.7 ± 0.2 |
|                      | #C11bt-2 | 68.6 ± 0.2 | 69.6 ± 0.2 |
|                      | #C11bt-3 | 68.5 ± 0.1 | 69.6 ± 0.1 |
|                      | PMbt1 | 65.0 ± 0.2 | 298.2 ± 4.3 | 66.0 ± 0.2 |
|                      | PMbt2 | 64.9 ± 0.1 | 66.0 ± 0.1 |
| Baksi (1994) (FCbt = 27.95 Ma) | JEB339 | 65.6 ± 1.0 | 296.3 ± 3.2 | 67.0 ± 1.0 |
| Hofmann et al. (2000) (Hb3gr = 1072 Ma) | JW2 | 65.7* ± 1.0 | 291.8 ± 3.6 | 66.4 ± 1.0 |
|                      | JW4 | 65.0 ± 1.5 | 292.9 ± 7 | 65.7 ± 1.5 |
|                      | JW5 | 66.2* ± 1.2 | 279.8 ± 14.4 | 66.9 ± 1.2 |
|                      | JW6 | 65.7 ± 1.3 | 305.5 ± 14.6 | 66.4 ± 1.3 |
|                      | JW7 | 66.5* ± 1.4 | 289.5 ± 3.8 | 67.2 ± 1.4 |
|                      | MA2 | 63.0* ± 2.0 | 311.6 ± 16 | 63.7 ± 2.0 |
|                      | D90 | 65.2 ± 0.4 | 431 ± 660 | 65.9 ± 0.4 |
| Courtillot et al. (2000) (Hb3gr = 1072 Ma) | AJ4 | 64.6* ± 0.8 | 303.4 ± 3.2 | 65.3 ± 0.8 |
|                      | AJ3 | 66.8 ± 0.5 | 67.5 ± 0.5 |
|                      | AJ1 | 66.3* ± 0.7 | 299.4 ± 1.2 | 67.0 ± 0.7 |
|                      | AJ11 | 67.0 ± 0.6 | 304.4 ± 10.2 | 67.7 ± 0.6 |
| Mahoney et al. (2002) (FCT-3 = 28.04 Ma) | D1 | 65.5 ± 1.1 | 300.9 ± 27.3 | 66.7 ± 1.1 |
|                      | B4 | 65.0 ± 1.2 | 292.1 ± 18.8 | 66.1 ± 1.2 |
| Knight et al. (2005) (FCs = 28.02 Ma) | RA99.1B | 65.0 ± 1.6 | 287 ± 12 | 65.6 ± 1.6 |
|                      | RA00.1B | 62.7 ± 2.3 | 380 ± 130 | 63.3 ± 2.3 |
|                      | RA991BB | 69.0* ± 4.0 | 280 ± 15 | 69.6 ± 4.0 |
|                      | RA99.02 | 65.2* ± 0.5 | 297 ± 1 | 65.8 ± 0.5 |
|                      | RA99.06 | 64.6 ± 1.9 | 300 ± 30 | 65.2 ± 1.9 |
|                      | RA99.06 | 61.8* ± 1.3 | 299 ± 3 | 62.4 ± 1.3 |
|                      | RA99.11 | 63.7 ± 0.8 | 296 ± 17 | 64.3 ± 0.8 |
|                      | RA99.12A | 64.6 ± 0.8 | 286 ± 20 | 65.2 ± 0.8 |
|                      | RA99.12B | 62.7* ± 2.0 | 350 ± 50 | 63.3 ± 2.0 |
|                      | RA99.14 | 64.3 ± 0.4 | 280 ± 20 | 64.9 ± 0.4 |
|                      | RA99.23 | 64.7 ± 0.4 | 289 ± 19 | 65.3 ± 0.4 |
| Baksi (2013) (FCs = 28.03 Ma) | D-921 | 61.2* ± 1.6 | 495 ± 16 | 61.8 ± 1.6 |
| Shrivastava et al. (2015) (FCs = 28.201 Ma) | SKF10 | 64.1 ± 0.7 | 294.7 ± 15.8 | 64.3 ± 0.7 |
|                      | MK6 | 64.9 ± 1.2 | 304.2 ± 50.1 | 65.1 ± 1.2 |
|                      | MK2 | 63.2 ± 1.2 | 262.2 ± 55.1 | 63.4 ± 1.2 |
|                      | NL-F2/S2 | 63.7 ± 1.2 | 301.5 ± 6.6 | 63.9 ± 1.2 |
|                      | PLB-F12/ | 63.8 ± 0.5 | 290.0 ± 24.9 | 64.0 ± 0.5 |
| Renne et al. (2015) (FCs = 28.294 Ma) | MG8C | 66.2 ± 0.3 | 66.2 ± 0.3 |
|                      | MAT14-5 | 66.2 ± 0.4 | 66.2 ± 0.4 |
|                      | MSJ14-4 | 65.2 ± 0.3 | 65.2 ± 0.3 |
|                      | AMB14-9 | 65.7 ± 0.3 | 65.7 ± 0.3 |
|                      | BOR14-1 | 66.2 ± 0.2 | 66.2 ± 0.2 |
|                      | MG7 | 66.3 ± 0.2 | 66.3 ± 0.2 |
|                      | MSJ14-6B | 66.3 ± 0.2 | 66.3 ± 0.2 |
|                      | KAS14-1A | 66.4 ± 0.2 | 66.4 ± 0.2 |
| Lehmann et al. (2010) (Hb3gr = 1072 Ma) | DEBS/106 | 65.4 ± 3.6 | 66.1 ± 3.6 |
|                      | DEBS/114 | 67.6 ± 1.7 | 68.3 ± 1.7 |
|                      | DEBS/56 | 66.5 ± 1.0 | 67.2 ± 1.0 |
|                      | K-4 | 59.7 ± 2.1 | 60.4 ± 2.1 |
|                      | K-8 | 64.0 ± 1.9 | 64.7 ± 1.9 |

Compilation of reliable $^{40}$Ar/$^{36}$Ar ages from the Deccan Traps and rocks linked to the Deccan volcanism; only ages obtained with at least 70% of the released $^{39}$Ar are reported. Age recalculation after Renne et al. (2010; 2011). Plateau or $^{39}$Ar/$^{40}$Ar–$^{36}$Ar/$^{40}$Ar isochron (*) ages are reported. $^{40}$Ar/$^{36}$Ar intercept is the intercept value calculated from $^{36}$Ar/$^{39}$Ar–$^{36}$Ar/$^{39}$Ar isochron.
data are not discussed further. All age uncertainties are given at the 2σ level (Table 1).

The K/Ar data for plagioclase from basaltic lavas of the Western Ghats sequence suggested apparent ages ranging from 64.5 ± 0.6 to 64.8 ± 0.6 Ma (Chenet et al. 2007). However, the K/Ar method yields ages that are significantly different from 40Ar/39Ar or U/Pb zircon ages on the same lava flow formations (see below) and it furthermore does not allow a test of the goodness of the results, in terms of detection of excess Ar, or determining in which measure the alteration affected the apparent age. Therefore, we will not consider such K/Ar data further.

Retained ages

The geochronological data suggest that the total Deccan activity lasted some 4 myr. The oldest activity occurred in the north. Two intrusive alkaline complexes from the Cambay graben (Samru Dandali and Mundwara) yielded 40Ar/39Ar ages of 69.62 ± 0.08 Ma and 69.58 ± 0.16 Ma respectively on biotite, making them the likely first continental phase of Deccan magmatism (Basu et al. 1993). Basu et al. obtained an age of 66.04 ± 0.16 Ma on biotite for an olivine gabbro from the Phenai Mata complex, Narmada valley (Gujarat). Further evidence for an early Deccan activity was obtained for alkali-basaltic lava flows from the Anjar Traps (Kutch region, dated at 67.47 ± 0.30–67.67 ± 0.60 Ma on whole-rock and plagioclase separates by Courtillot et al. (2000), and for diamondiferous Mainpur field kimberlites, Bastar Craton (central India), dated at 67.37 ± 0.80 and 62.77 ± 1.40 Ma (40Ar/39Ar on whole-rock; Lehmann et al. 2010).

Most geochronological investigations have focused on the Western Ghats lava pile, the most voluminous and complete sequence in the Deccan Traps. 40Ar/39Ar analyses have revealed that at least 1700 m of the lava sequence were erupted in a short interval of c. 1 myr (Baksi 1994; Hofmann et al. 2000), with the ages of the bottom (mean age 66.07 ± 0.70 Ma) being indistinguishable from those at the top (65.87 ± 0.4 Ma; Hofmann et al. 2000). Evidence for a relatively short eruption history has been recently confirmed by Schoene et al. (2015), who obtained U/Pb ages on single zircon (2–8 data per sample) ranging from 66.29 ± 0.03 Ma (lowest lava flow unit, Jawhar formation) to 65.53 ± 0.03 Ma (topmost lava flow unit, Mahabaleshwar formation). New 40Ar/39Ar ages by Renne et al. (2015) on plagioclase are virtually indistinguishable from the U/Pb ages of Schoene et al. (2015) and thus support the same eruption history for the Western Ghats sequence, lasting from 66.38 ± 0.10 to 65.62 ± 0.08 Ma. In particular, both the U/Pb ages of Schoene et al. (2015) and the 40Ar/39Ar ages of Renne et al. (2015) suggest that the last two flow units (Ambenali and Mahabaleshwar) were erupted after the K–Pg boundary, dated at 66.04 ± 0.09 Ma by Renne et al. (2015).

Lava flows cropping out along the eastern coast of India in the Rajahmundry traps yielded ages (65.33 ± 0.50 Ma, 40Ar/39Ar on plagioclase; Knight et al. 2003) similar to those of the upper Western Ghats formations (Ambenali and Mahabaleshwar). Rajahmundry and Western Ghats lavas are also correlated on the basis of their geochemical characteristics and remanent magnetization (Knight et al. 2003). Basaltic lava flows from the Mandla lobe, located on the eastern margin of the main Deccan volcanic province, have been dated by Shrivastava et al. (2015). Those researchers provided a weighted mean 40Ar/39Ar age for the section (64.42 ± 0.33 Ma) and a geochemical correlation of the Mandla lobe lavas with the uppermost units of the Western Ghats succession (Poladpur–Ambenali–Mahabaleshwar formations). This suggests that the post-K–Pg phase of flood basalt activity erupted over much of the province (Shrivastava et al. 2015).

In general, these geochronological data suggest that the bulk of the Deccan was emplaced between c. 67 and 65 Ma, with the exception of some early alkaline activity in the far north (Cambay graben) at c. 69 Ma. It should be noted that 40Ar/39Ar ages on plagioclase (typically for felsic lavas) yield relatively large errors, which makes it difficult to confirm or exclude any time-related southward migration of the magmatism. A better precision can be achieved for phases included in alkaline rocks, but those are rare and very localized. Palaeomagnetic and biostratigraphic correlations provide additional constraints and indicate that the general evolution of the Deccan volcanism occurred in three distinct phases (Chenet et al. 2009; Keller et al. 2011): a first phase at the boundary between magnetostriatigraphic chron C30r and C30n and covering the northern half of the Deccan; a second phase starting in chron C29r, straddling the K–Pg boundary and constituting about the 80% of the total volume of the province; and a third, waning phase lasting until chron C29n.

Sampling

For the present study, we sampled alkaline and tholeiitic rocks from the northern Deccan. Sampling was focused in the western Narmada rift region, in an area north and west of the Amba Dongar carbonatite complex (Fig. 1b). The Narmada rift is characterized by an east–west-trending tholeiitic dyke swarm cross-cutting the flood basalt sequence and extending across Peninsular India, and by alkaline dykes with various directions (north–south, east–west, NNE–SSW). Intrusive bodies are comprised of both alkaline and tholeiitic rocks (essentially gabros to syenites), such as the Phenai Mata intrusion (Gwalani et al. 1993; Fig. 1b). The Phenai Mata complex shows the association of alkaline rocks and a layered tholeiitic intrusion (Sukheswala & Sethna 1973; Gwalani et al. 1993), and the surrounding areas are mainly constituted by phonolite, lamprophyre and nepheline-syenite, which form plugs and dykes, with ENE–WSW and NWN–ESE trend. Samples of alkaline (PL3) and tholeiitic gabro (PL9, PL20), as well as a nepheline-syenite (PL2) and a lamprophyric dyke (PL36), have been analysed from this region.

Samples were also collected from the Rajpipla area, where some of the oldest Deccan lavas should be expected (e.g. Chenet et al. 2007). This area shows a succession of early tholeiitic lava flows over lain by K-rich alkaline flows, which form the main exposed sequence, in turn cut by late tholeiitic dykes (Krishnamurthy & Cox 1980). The Rajpipla basalt sample PL54 that has been dated here is a tholeiitic lava that belongs to the early phase of this region.

The Pavagadh hill is an outlier cropping out to the north of the Narmada–Tapti rift. The mafic lavas have a peculiar geochemical and isotopic composition having no equivalent in the bulk of the Deccan sequence but resembling some Reunion Island lavas (see Melluso et al. 2006). The Pavagadh section (Melluso et al. 1995; Sheth & Melluso 2008) consists of a 550 m-thick sequence of igneous rocks ranging from alkali olivine basalt (PL61) to rhyolite lavas often with glassy textures (i.e. sample PL63).

Methods

40Ar/39Ar dating was carried out on eight mineral separate samples: four biotites, one amphibole and three plagioclase separates (Table 2). Each sample was carefully hand-picked under the binocular microscope and washed with distilled water and methanol.

Samples were loaded into eight large wells of one aluminium disc of 1.9 cm diameter and 0.3 cm depth (one for plagioclase and one for biotite). These wells were bracketed by small wells that included Fish Canyon sanidine (FCs) used as a neutron fluence monitor, for which an age of 28.294 ± 0.036 Ma (1σ) was adopted (Renne et al. 2011). The discs were Cd-shielded (to minimize undesirable nuclear interference reactions) and irradiated for 40 h in the US Geological Survey nuclear reactor (Denver, CO) in...
$^{36}\text{Ar}/^{40}\text{Ar}$ isochron age obtained for Narmada samples

Table 2. New $^{40}\text{Ar}/^{39}\text{Ar}$ data: summary table indicating plateau age and $^{39}\text{Ar}/^{40}\text{Ar}$ – $^{36}\text{Ar}/^{40}\text{Ar}$ isochron age.

| Sample | Locality | Mineral | Age ± 2σ (Ma) | MSWD | Probability (%) | $S$ (%) | $\text{Ar}^{39}/\text{Ar}^{40}$ Age ± 2σ (Ma) | MSWD | Probability (%) | $S$ (%) | $\text{Ar}^{36}/\text{Ar}^{40}$ intercept ± 2σ |
|--------|----------|---------|---------------|------|-----------------|--------|-----------------|------|-----------------|--------|-----------------|
| PL2    | Phenai Mata | Amphibole | 66.60 ± 0.35 | 0.79 | 65 | 95.40 | 66.87 ± 0.32 | 0.9 | 49 | 99.29 | 0.79 | 65 | 95.40 |
| PL3    | Phenai Mata | Biotite | 66.24 ± 0.37 | 0.36 | 36 | 68.87 | 324.40 ± 13.10 | 1.01 | 40 | 97.72 | 0.36 | 36 | 68.87 |
| PL9    | Phenai Mata | Biotite | 66.43 ± 0.41 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |
| PL36   | Dongargaon | Biotite | 65.25 ± 0.29 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |
| PL36   | Dongargaon | Plagioclase | 65.20 ± 0.32 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |
| PL54   | Rajpipla | Plagioclase | 65.00 ± 0.42 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |
| PL61   | Mount Pavagadh | Plagioclase | 65.94 ± 0.49 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |
| PL63   | Mount Pavagadh | Plagioclase | 65.94 ± 1.08 | 0.36 | 36 | 68.87 | 65.94 ± 1.58 | 0.53 | 92 | 64 | 86 | 300.92 ± 41.05 |

$^{36}\text{Ar}/^{37}\text{Ar}$ ratios (0.022 ± 0.003) owing to the scarcity of fresh crystals and to their low K/Ca ratios as calculated from $^{39}\text{Ar}/^{37}\text{Ar}$ are generally consistent with initial argon being of atmospheric origin, thus indicating that no excess Ar was present. Only the amphibole of sample PL2 has excess Ar ($^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 324 ± 13, significantly higher than the air value of 295.5), suggesting that for this sample the $^{39}\text{Ar}/^{40}\text{Ar}$ isochron age (66.60 ± 0.35 Ma) is more reliable than the plateau age (66.87 ± 0.32 Ma). In general, K/Ca ratios as calculated from $^{39}\text{Ar}/^{37}\text{Ar}$ are consistent with the chemical compositions of the analysed phases as determined by electron microprobe measurements, and the presence of atmospheric argon suggests that for this sample the $^{39}\text{Ar}/^{40}\text{Ar}$ isochron age is more reliable than the plateau age. All uncertainties are included in the calculation following the Monte Carlo simulation error calculation of Renne et al. (2010).
of secondary phases such as sericite or adularia (with higher K/Ca) can be ruled out.

The four samples from Phenai Mata provided robust plateau (PL3, PL9, PL20; biotite) or 39Ar/40Ar–36Ar/40Ar isochron (PL2; amphibole) ages, which are indistinguishable at the 2σ level (from 66.60 ± 0.35 to 66.24 ± 0.37 Ma; Table 2) and yielded a mean age of 66.42 ± 0.17 Ma (MSWD = 0.73; P = 0.53) for the emplacement of the Phenai Mata intrusion. Notably, these ages are indistinguishable from those (66.01 ± 0.11 Ma) obtained by Basu et al. (1993) on a sample equivalent to sample PL9 dated in the present study.

The lamprophyric dyke PL36 (sampled east of Phenai Mata; Fig. 1b) also yielded a well-defined plateau age on biotite (65.25 ± 0.29 Ma), which is significantly younger than those of Phenai Mata rocks. A significantly younger age (64.9 ± 0.8 Ma) was obtained also for a plagioclase (An37–53, K/Ca = 0.023–0.135) separate from the rhyolite PL63 (Mount Pavagadh). Finally, plateau ages (65.9 ± 1.7 Ma and 66.4 ± 2.8 Ma, respectively) were obtained for plagioclase in tholeiitic samples of Rajpipla (basaltic lava flow PL54; An62–76, K/Ca = 0.007–0.025) and Mount Pavagadh (basaltic dyke PL61; An60–69, K/Ca = 0.022–0.035).

Fig. 2. (a) 39Ar/40Ar–36Ar/40Ar isochron plot for sample PL2; black squares, plateau data points; grey squares, non-plateau data points. (b–h) Apparent age spectra of the samples with no excess Ar; plateau ages are indicated by the arrow; MSWD, mean square of the weighted deviates; P, probability of fit. K/Ca data are shown and compared with the measured EMPA values (in parentheses).
Age of magmatism in the Narmada valley

The new $^{40}$Ar/$^{39}$Ar data indicate that magmatic activity in the northern Deccan (Narmada valley) continued from 66.60 ± 0.35 to 64.9 ± 0.8 Ma and is generally synchronous with the main phase or with a late phase of Deccan volcanism as well as with some of the Rajahmundry lava flows (Figs 2 and 3). In particular, alkaline and tholeiitic rocks of the Phenai Mata intrusion were emplaced in a short time span at c. 66.4 Ma. Globally, these ages show that the Phenai Mata magmatism was contemporaneous with the onset of Deccan activity from the Western Ghats. In contrast, a slightly younger magmatic phase characterizes alkaline dykes (such as the lamprophyre PL36; 65.25 ± 0.29 Ma) and the Pavagadh complex (64.9 ± 0.8 Ma), which are indistinguishable in age from the late Western Ghats flows (Schoene et al. 2015).

Because our ages for the northern Deccan are indistinguishable from those of the Western Ghats, they are not consistent with a southward migration of the volcanism owing to northward movement of the Indian plate above a fixed Reunion hotspot (Figs 1 and 4). In particular, our ages for the Pavagadh complex and for alkaline magmatism east of Phenai Mata show that late-phase magmatism also occurred in the northern regions of the Deccan province (with alkaline igneous rocks). Therefore, it is suggested that the evolution of the magmatism in this large area reflects a pulsating mantle melting regime with magmatism active for well over 1 myr, rather than a linear evolution of a progressively southward migrating magmatism.

Based on our new data and on the recalculated and filtered $^{40}$Ar/$^{39}$Ar ages from previous studies, we can provide further constraints for the duration of the Deccan volcanism and its belonging to the magnetic chrons C31–C29. In particular, the recalculated ages have shown that the first phase of alkaline Deccan magmatism (Sarnu and Mundwara complexes in the northern Deccan; Basu et al. 1993) can be placed at the boundary between the magnetic chrons C31r and C31n. We have provided the first age for the Rajpipla magmatism (PL54: 65.86 ± 1.68 Ma), and its maximum age (67.54 Ma) suggests that the activity in the northern Deccan may have started within or after chron C30n (c. 67.5 Ma) and not at the boundary between chron C30r and C30n (>68 Ma) as previously suggested (Chenet et al. 2008, 2009).
The analysed Rajpipla basalt (PL54) and Pavagadh rhyolite (PL63; 64.9 ± 0.8 Ma) indicate a maximum and minimum duration of the tholeiitic Deccan magmatism of c. 3 myr and <1 myr, respectively. Conversely, alkaline magmatism lasted c. 4 myr, from 69.62 ± 0.08 Ma (Cambai Graben; Basu et al. 1993) to 65.25 ± 0.29 Ma (PL36), but it should be noted that high-quality age data for the alkaline magmatism are limited to the northern Deccan alkaline complexes.

**Implications for the genesis of alkaline and tholeiitic Deccan magmatism**

Alkaline samples are a distinctive feature of the Deccan Traps and are often thought to constitute the early and late phase of the volcanism (Basu et al. 1993). In general, alkaline and tholeiitic magmas require different degrees of partial melting and mantle sources (e.g. Simonetti et al. 1998). In a mantle plume scenario, such variations are expected to be time-related, with alkaline magmatism preceding and possibly following the main phase of tholeiitic magmatism such as observed for the Hawai‘i hotspot (e.g. Wyllie 1988). However, the geochronological data do not support such a model for the Deccan. Although we cannot discriminate between the age of, for example, Phenai Mata alkaline and tholeiitic rocks, our data show that alkaline and tholeiitic rocks of early (c. 66.4 Ma) and late phase (c. 65 Ma) both occur in the northern Deccan. As both alkaline and tholeiitic rocks have been produced during both early and late phases in a relatively small region, the possibility for them to have formed from the same mantle source is unlikely and the existence of different mantle sources for synchronous alkaline and tholeiitic magmas is required, as already suggested by Simonetti et al. (1998) and Melluso et al. (2002, 2006). Those researchers invoked, besides the Reunion plume, the significant involvement of the subcontinental lithospheric mantle for the generation of Deccan magmatism.

**Implications for the age of the Deccan magmatism v. the K–Pg boundary**

One of the most important mass extinctions in Earth’s history has been identified at the K–Pg boundary, but its causes are still a matter of debate. Two events are invoked as the principal causes for the extinction, owing to their synchronicity with the K–Pg boundary: the Deccan volcanism and the Chicxulub bolide impact in the Yucatan Peninsula (Alvarez et al. 1980; Schulte et al. 2010a). As discussed above, the main phase of Deccan volcanism occurred at c. 66 Ma with main activity starting some 0.5 myr before and ending after the K–Pg boundary and the Chicxulub impact (dated at 66.04 ± 0.09 Ma and 66.04 ± 0.05 Ma, respectively; Renne et al. 2013; Sprain et al. 2015). As pointed out by Renne et al. (2015) and Richards et al. (2015), a change in eruption style and rate of Deccan volcanism occurred at the K–Pg boundary and was possibly caused by the Chicxulub impact.

The debate about the main causes of the end-Cretaceous extinction is still very lively (Archibald et al. 2010; Courtillot & Fluteau 2010; Keller et al. 2010; Schulte et al. 2010a,b). Stratigraphic and geochronological studies constrain the synchronicity of the Chicxulub impact, marked worldwide by a razor-sharp iridium spike (Alvarez et al. 1980; Smit & Hertogen 1980; Almy 2008; Schulte et al. 2010a; Renne et al. 2013; but see also contrasting results of Keller et al. 2011). Degassing of the impacted sedimentary strata released 100–500 Gt of SO$_2$ (Pierzazo et al. 2003), which, combined with the effects of dust release, led to a sudden global cooling of possibly up to 10°C (Pope et al. 1997; Schulte et al. 2010a). These and other effects of the Chicxulub impact (e.g. tsunamis and large-magnitude earthquakes) have been proposed as main devastating causes of the sudden and widespread extinction of the latest Mesozoic fauna and flora (e.g. Vajda et al. 2001; Bown 2005; MacLeod et al. 2007). Other studies have noted, however, a progressively more stressed global environment during the Maastrichtian that heralded the K–Pg turnover before the Chicxulub impact (e.g. Keller et al. 2008, 2009). The Late Maastrichtian events are characterized by global climate instability (abrupt cooling and sea-level drop; Li & Keller 1998; Scheffler et al. 2009), and a decrease of vertebrates (e.g. Barrett et al. 2009) and planktic foraminifera species (e.g. Globotruncanidae) started in chron C30n (Keller et al. 2008, 2011). It is this early phase of global climate instability and biotic reduction events as well as a delayed recovery during the early Palaeogene that may well be explained by the Deccan volcanism and cannot be attributed to the Chicxulub impact.

The recalculated ages and our new data allow us to identify two early magmatic pulses (at c. 69.5 and 67.5 Ma) in the Deccan Traps before the K–Pg boundary, followed by a peak activity straddling the boundary at c. 66 Ma (comprising the Phenai Mata intrusion) and followed by a prolonged late activity (Fig. 3). The two early magmatic pulses at c. 69 and c. 67 Ma should correspond to the magnetic chronos C31n and C30n. This early Deccan magmatism was recorded by a negative $^{187}$Os/$^{188}$Os excursion in Maastrichtian ocean sediments (Ravizza & Peucker-Ehrenbrink 2003). Moreover, the late phase of Deccan volcanism, defined by our analyses for the northern Deccan (samples such as PL61 and PL36) as well as by the ages for the Mahabaleshwar flows (66.55 ± 0.03 Ma; Schoene et al. 2015) and the Rajahmundry Traps (65.33 ± 0.50 Ma; Knight et al. 2003), could be responsible for the delayed biotic recovery after the K–Pg boundary, as observed in the Danian foraminifera assemblages in the intertrap sediments at Jhilimi and Rajahmundry (Keller et al. 2008, 2009) and in the proliferation of the disaster opportunist survivor species such as *Guembelitria cretacea* (Keller 2003; Keller & Pardo 2004). Therefore, the observations that the onset of the end-Cretaceous mass extinction can be placed within chron C30n and thus coincides with the early Deccan volcanism and that a slow recovery after the K–Pg mass extinction may be associated with a slow waning of late Deccan volcanism strongly underline the role of Deccan volcanism in controlling biotic and climatic changes from the end of the Cretaceous into the early Palaeogene. In general, comparison between mass extinctions and flood basalt emplacements in the geological record back to the Cambrian showed that this association is recurrent and is statistically unlikely to be due to random chance (Jourdan et al. 2014). Furthermore, no other impact–extinction pairs have been yet identified in the geological record (Jourdan 2012).

**Conclusions**

The Deccan Traps are formed by volumetrically dominant tholeiitic rocks and by less abundant, but important alkaline rocks. New $^{40}$Ar/$^{39}$Ar ages on such rocks cropping out in the northern portion of the province (Narmada valley) provide new constraints on the relationship between the two magma series and on the evolution of Deccan magmatism in general. We have provided a new filtered dataset with the most reliable ages available for the Deccan Traps.

The recalculated $^{40}$Ar/$^{39}$Ar ages show that the magmatic activity started at the boundary between magnetic chronos C31r and C31n with the emplacement of the Sarnu Danduli and Mundwara complexes, and that Deccan magmatism lasted at least 4 myr. The new data along with previous data show that alkaline magmatism is not confined to the early and late phase of the evolution of the province, but occurred also within the main phase, when the most voluminous lava sequence (the Western Ghats) was erupted, thus pointing towards two distinct mantle sources responsible for synchronous production of alkaline and tholeiitic magmas. Moreover, the distribution of the new data is not consistent with a simple southward migration of the volcanism, as
younger rocks (such as Mount Pavagadh) are still well preserved in the northern Deccan. This shows that Deccan magmatism from the Namada rift to the Western Ghats and the Rajahmundry Traps was essentially synchronous, straddling the K–Pg boundary. In contrast, the most precise data on alkaline samples indicate that ages significantly older than 67 Ma are limited to the northwestern sector of the Deccan (Fig. 4).

In addition, the age of the Deccan Traps suggests a causal link between the emplacement of the province and the K–Pg mass extinction. The onset of the mass extinction can be placed at the boundary between chron C30n and C29r, together with Deccan volcanism. The Deccan is also compatible with the biotic evolution after the K–Pg boundary and the Chicxulub impact.

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References

Alroy, J. 2008. Dynamics of origination and extinction in the marine fossil record. Proceedings of the National Academy of Sciences of the USA, 105 (Supplement 1), 11536–11542.

Alvarez, L.W., Alvarez, W., Asaro, F. & Michel, H.V. 1980. Extraterrestrial cause for the Cretaceous–Tertiary extinction: experimental results and theoretical interpretation. Science, 208, 1095–1108.

Archibald, J.D., Clemens, W.A., et al. 2010. Cretaceous extinctions: multiple causes. Science, 328, 973.

Baksi, A.K. 1994. Geochronological studies on whole-rock basalts, Deccan Traps, India: evaluation of the timing of volcanism relative to the K–T boundary. Earth and Planetary Science Letters, 121, 43–56.

Baksi, A.K. 2007. A quantitative tool for detecting alteration in undisturbed rocks and minerals—II application to argon ages related to hotspots. Geological Society of America Special Paper, 430, 305–334.

Baksi, A.J. 2014. The Deccan Trap–Cretaceous–Palaeogene boundary connection; new 40Ar/39Ar ages and critical assessment of existing argon data pertinent to this hypothesis. Journal of Asian Earth Sciences, 84, 9–23.

Barrett, P.M., McGowan, A.J. & Page, V. 2009. Dinosaur diversity and the rock record. Proceedings of the Royal Society of London, Series B, 276, 2667–2674.

Basu, A.R., Renne, P.R., Dasgupta, D.K., Teichmann, F. & Poreda, R.J. 1993. Early and late alkali igneous pulses and a high-h1e He plume origin for the Deccan flood basalts. Science, 261, 902–906.

Bowen, P. 2005. Selective calcareous nanoplankton survivorship at the Cretaceous–Tertiary boundary. Geology, 33, 653–656.

Cande, S.C. & Kent, D.V. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research, 100, 6093–6095.

Chafe, A.N., Villa, I.M., Fluteau, F., Courtillot, V. & Subbarao, K.V. 2008. Determination of rapid Deccan eruptions across the Cretaceous–Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis of KTB age and short duration. Earth and Planetary Science Letters, 268, 293–311.

Chenet, A.L., Courtillot, V. & Fluteau, F. 2010. Cretaceous extinctions: the volcanic hypothesis. Science, 328, 973–974.

Chenet, A.L., Quidelleur, X., Courtillot, V. & Bajpai, S. 2007. New 40Ar/39Ar ages and critical assessment of existing argon data pertinent to this hypothesis. Journal of Asian Earth Sciences, 84, 9–23.

Courtillot, V., Fluteau, F., Courtillot, V., Bajpai, S. 2007. 40K/40Ar dating of the Main Deccan large igneous province: Further evidence of KT age and short duration. Earth and Planetary Science Letters, 263, 1–15.

Courtillot, V., Fluteau, F., Courtillot, V., Gerard, M. & Subbarao, K.V. 2008. Determination of rapid Deccan eruptions across the Cretaceous–Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section. Journal of Geophysical Research, 114, B06103.

Courtillot, V., Gallet, Y., et al. 2000. Cosmic markers, 40Ar/39Ar dating and paleomagnetism of the KT sections in the Anjar Area of the Deccan large igneous province. Earth and Planetary Science Letters, 182, 137–156.

Cucinelli, C., Demontevera, E.I., Shih, H., Pande, K. & Vijayan, A. 2015. 40Ar/39Ar geochronology and geochemistry of the Central Saurashtra mafic
Melluso, L., Sethna, S.F., D’Antonio, M., Javeri, P. & Bennio, L. 2002. Geochemistry and petrogenesis of sodic and potassic mafic alkaline rocks in the Deccan volcanic province, Mumbai area (India). Mineralogy and Petrology, 74, 323–342.

Melluso, L., Mahoney, J.J. & Dallai, L. 2006. Mantle sources and crustal input as recorded in high-Mg Deccan Traps basalts of Gujarat (India). Lithos, 89, 259–274.

Mitchell, C. & Widdowson, M. 1991. A geological map of the southern Deccan Traps, India and its structural implications. Journal of the Geological Society, London, 148, 495–505, http://doi.org/10.1144/gsjgs.148.3.0495.

Morgan, W.J. 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In: Emiliani, C. (ed.) The Sea, Vol. 7, Wiley, New York, 443–487.

Onstott, T.C., Phillips, D. & Pringle-Goodell, L. 1991. Laser microprobe measurement of chlorine and argon zonations in biotite. Chemical Geology, 90, 145–168.

Pande, K., Pattanayak, S.K., Subbarao, K.V., Navaneethakrishnan, P. & Venkatesan, T.R. 2004. 40Ar/39Ar age of a lava flow from the Bhimashankar Formation, Giravali Ghat, Deccan Traps. Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences), 113, 755–758.

Pierzch, E., Hahamann, A.N. & Sloan, L.C. 2003. Chixculub and climate: Radiative perturbations of impact-produced S-bearing gases. Astrobiology, 3, 99–117.

Pope, K.O., Baines, K.H., Ocampo, A.C. & Ivanov, B.A. 1997. Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact. Journal of Geophysical Research, 102, 21645–21664.

Ravizza, G. & Pesecker-Ehrenbrink, B. 2003. Chemostatigraphic evidence of Deccan volcanism from the marine osmium isotope record. Science, 302, 1392–1395.

Ray, J.S. 1998. Trace element and isotope evolution during concurrent assimilation, fractional crystallization, and liquid immiscibility of a carbonated silicate magma. Geochimica et Cosmochimica Acta, 62, 3301–3306.

Renne, P.R., Mundil, R., Balco, G., Min, K. & Ludwig, K.R. 2010. Joint determination of 4K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology. Geochimica et Cosmochimica Acta, 74, 5349–5367.

Renne, P.R., Mundil, R., Balco, G., Min, K. & Ludwig, K.R. 2011. Response to the comment by B. H. Shwarz et al. on “Joint determination of 4K decay constants and 40Ar*/40K for the Fish Canyon Sanidine standard, and improved accuracy for 40Ar/39Ar geochronology” by P. R. Renne (2010). Geochimica et Cosmochimica Acta, 75, 5097–5100.

Renne, P.R., Deino, A.L., et al. 2013. Time scales of critical events around the Cretaceous–Paleogene Boundary. Science, 339, 684–687.

Renne, P.R., Sprain, C.J., Richards, M.A., Self, S., Vanderkluysen, L. & Pande, K. 2015. State shift in Deccan volcanism at the Cretaceous–Paleogene boundary, possibly induced by impact. Science, 350, 76–78.

Richards, M.A., Alvarez, W., et al. 2015. Triggering of the largest Deccan eruptions by the Chixculub impact. Geological Society of America Bulletin, 127, 1507–1520.

Scheffer, M., Bascompte, J., et al. 2009. Early-warning signals for critical transitions. Nature, 461, 53–59.

Schoene, B., Samperton, K.M., et al. 2015. U–Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. Science, 347, 182–184.

Schulte, P., Alegret, A., et al. 2010a. The Chixculub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. Science, 327, 1214–1218.

Schulte, P., Alegret, A., et al. 2010b. Response to Archibald et al., Keller et al., and Courtillot & Fluteau. Science, 328, 975–976.

Self, S., Widdowson, M., Thordarson, T. & Jay, A.E. 2006. Volatile fluxes during flood basalt eruptions and potential effects on the global environment: A Deccan perspective. Earth and Planetary Science Letters, 248, 518–532.

Self, S., Blake, S., Sharma, K., Widdowson, M. & Sephton, S. 2008. Sulphur and chlorine in late Cretaceous Deccan magmas and eruptive gas release. Science, 319, 1664–1675.

Sheth, H.C. & Melluso, L. 2008. The Mount Pavagadh volcanic suite, Deccan Traps: geochemical stratigraphy and magmatic evolution. Journal of Asian Earth Sciences, 32, 5–21.

Sheth, H.C. & Pandle, K. 2014. Geological and 40Ar/39Ar age constraints on late-stage Deccan rhyolitic volcanism, inter-volcanic sedimentation, and the Panvel flexure from the Dongri area, Mumbai. Journal of Asian Earth Sciences, 84, 167–175.

Sheth, H.C., Pandle, K. & Bhutani, R. 2001. 40Ar/39Ar ages of Bombay trachytes: evidence for a Palaeocene phase of Deccan volcanism. Geophysical Research Letters, 28, 3513–3516.

Shrivastava, J.P., Duncan, R.A. & Kashyap, M. 2015. Post-K/PB younger 40Ar/39Ar ages of the Mandla lavas: Implications for the duration of the Deccan volcanism. Lithos, 224–225, 214–224.

Simonetti, A., Goldstein, S.L., Schindlberger, S.S. & Viladkar, S.G. 1998. Geochemical and Nd, Pb, and Sr isotope data from Deccan alkaline complexes—implications for mantle sources and plume–lithosphere interaction. Journal of Petrology, 39, 1847–1864.

Smit, J. & Hertogen, J. 1980. An extraterrestrial event at the Cretaceous–Tertiary boundary. Nature, 285, 198–200.

Spell, T.L. & McDougall, I. 2003. Characterization and calibration of 40Ar/39Ar dating standards. Chemical Geology, 198, 189–211.

Sprain, C.J., Renne, P.R., Wilson, G.P. & Clemens, W.A. 2015. High-resolution chronostratigraphy of the terrestrial Cretaceous–Paleogene transition and recovery interval in the Hell Creek region, Montana. Geological Society of America Bulletin, 127, 393–409.

Sukheswala, R.N. & Sethna, S.F. 1973. Oversaturated and undersaturated differentiates in the theoleitic igneous complex of Pheni Mata, Baroda District, Gujarat State, India. Neues Jahrbuch für Mineralogie, Abhandlungen, 118, 159–176.

Vajda, V., Raine, J.J. & Hollins, C.J. 2001. Indication of global deforestation at the Cretaceous–Tertiary boundary by New Zealand fern spire. Science, 294, 1700–1702.

Vanderkluysen, L., Mahoney, J.J., Hooper, P.R., Sheth, H.C. & Ray, R. 2011. The feeder system of the Deccan Traps (India): insights from dike geochemistry. Journal of Petrology, 52, 315–343.

Venkatesan, T.R., Pandle, K. & Gopalak, K. 1993. Did Deccan volcanism pre-date the Cretaceous–Tertiary transition? Earth and Planetary Science Letters, 19, 181–189.

Venkatesan, T.R., Pandle, K. & Ghevariya, Z.G. 1996. 40Ar/39Ar ages of Anjar Traps, western Deccan province (India) and its relation to the Cretaceous–Tertiary Boundary events. Current Science, 70, 990–996.

Watts, A.B. & Cox, K.G. 1989. The Deccan Traps: an interpretation in terms of progressive lithospheric flexure in response to a migrating load. Earth and Planetary Science Letters, 93, 85–97.

Wotzlaw, J.F., Schaltegger, U., Frick, D.A., Dunan, M.A., Gerdes, A. & Günther, D. 2013. Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. Geology, 41, 867–870.

Wyllie, P.J. 1988. Solidus curves, mantle plumes, and magma generation beneath Hawaii. Journal of Geophysical Research, 93, 4171–4181.