Emplacement of Amba Dongar carbonatite-alkaline complex at Cretaceous/Tertiary boundary: Evidence from ^{40}Ar-^{39}Ar chronology

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^{40}Ar-^{39}Ar analyses of three fresh alkaline rock samples and a phlogopite separate from a carbonatite from Amba Dongar carbonatite-alkaline complex of the Deccan Flood Basalt Province, India, yield indistinguishable precise plateau ages of 64.8 ± 0.6, 64.7 ± 0.5, 65.5 ± 0.8 and 65.3 ± 0.6 Ma, giving a mean plateau age of 65.0 ± 0.3 Ma, which is the age of emplacement of this complex. This age implies contemporaneity of Amba Dongar with several other carbonatite-alkaline activities of Chhota Udaipur subprovince and is consistent with their Reunion-Deccan plume origin hypothesis. The emplacement of these complexes at 65 Ma makes them very significant in the ongoing debate on the K/T extinctions owing to their capacity to rapidly inject a substantial amount of CO_2 and SO_2 into the atmosphere.

1. Introduction

The Amba Dongar carbonatite-alkaline complex, the first carbonatite complex to be identified in Asia (Sukheswala and Udas 1963), is located 2 km north of the Narmada river in Baroda district of Gujarat state and is a part of a large alkaline district of Chhota Udaipur (Sukheswala and Viladkar 1978). The rocks of this complex intrude into the Precambrian basement gneisses (Aravallis), Cretaceous Bagh sediments (sandstones and limestones) and some earlier flows of Deccan tholeiites. The general belief is that the Amba Dongar alkaline complex, like Phenai Mata of the same alkaline province (Chhota Udaipur), represents one of the late magmatic pulses of the Deccan flood basalts (Basu *et al* 1993). However there is no unambiguous age data in support of this hypothesis. Very early attempts by Deans and Powell (1968) and Deans *et al* (1973) to date the pyroxenes from nephelinites and two feldspars from potash fenites, using K-Ar method of dating, yielded varying ages of 37.5±2.5 Ma, 61±2 Ma and 76±2 Ma, respectively. Basu *et al* (1993) reported an ^{40}Ar-^{39}Ar age of 65 Ma (by dating the olivine gabbro) for the Phenai Mata alkaline complex, which is geographically close to Amba Dongar and is a part of the Chhota Udaipur alkaline district. However, it has so far not been clearly established whether Phenai Mata and Amba Dongar are temporally related. To establish the temporal relationship between the Amba Dongar alkaline complex and the Deccan Traps, precise ^{40}Ar-^{39}Ar dating of samples from Amba Dongar was undertaken. This would also allow one to assess the postulated relationship of these carbonatite complex with the Reunion-Deccan plume activity.

2. Geology and earlier work

The Amba Dongar complex is characterized by concentric ring dykes of carbonatites and carbonatite breccia with tholeiitic basalt at the central depression. The alkaline silicate rocks are present as plugs and dykes in the low surrounding area of the main ring dyke (figure 1). Fenitization, both potash and sodic, of the country rocks is an easily noticeable feature in this

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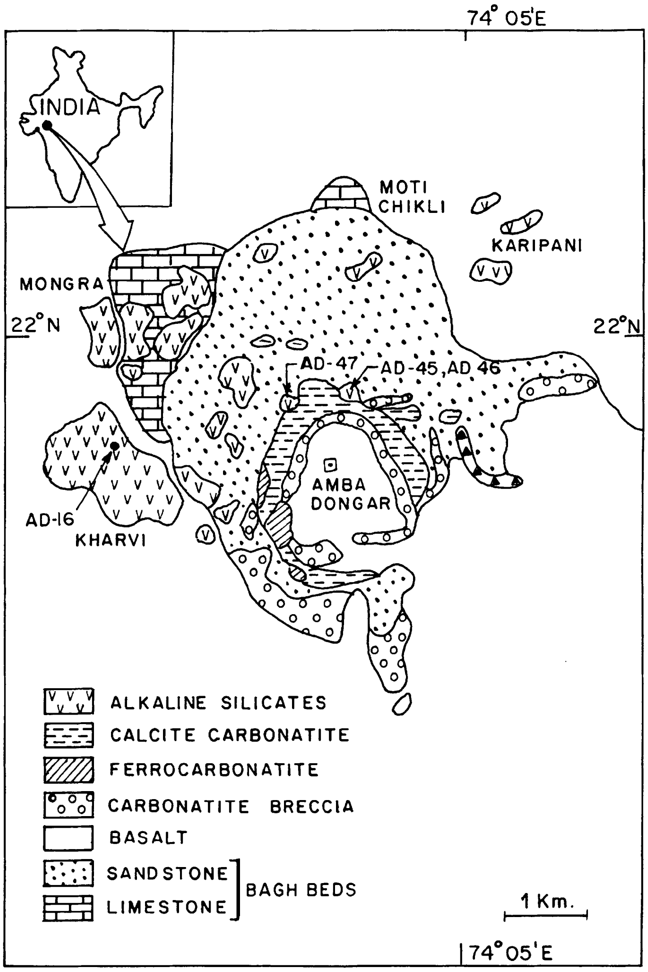

Figure 1. Geological map of Amba Dongar carbonatite-alkaline complex (after Viladkar 1996) showing various lithologies and sample locations.

complex. In addition, the carbonatites of this complex host a massive fluorite deposit. Carbonatites of this complex are of two types, calcite carbonatite and ferrocarbonatite. Calcite carbonatite forms the ring dyke with ferrocarbonatite as plugs within it. These also occur as numerous veins within earlier formed varieties. The alkaline silicate rocks have been identified as tinguaite, nephelinite and phonolite. Petrographic studies revealed that the calcite carbonatites vary from very coarse grained to fine grained with calcite as the major mineral (>70%) and magnetite, apatite and phlogopite as common accessories. Ferrocarbonatites are fine grained dark red coloured rocks in which ankerite is the major carbonate mineral. These rocks are invariably altered and contain lots of secondary products and are heavily affected by the fluorite mineralization. Alkaline silicate rocks contain nepheline, aegerine-aguite and melanite as phenocrysts, and analcite and calcite in the ground mass.

As mentioned above, earlier attempts to date the time of emplacement of Amba Dongar (by K-Ar method) have not been successful as the results showed a large variation in the age [from ~ 37 Ma to ~ 76 Ma; Deans *et al* (1973)]. We believe that the lower age (~ 37 Ma) reflects the loss of argon from the system, whereas the higher age (~ 76 Ma) possibly resulted from the selection of the wrong feldspar samples that might have been from a fenitized gneissic xenolith. However, it is very difficult to give a critical comment on such ages as the authors neither provide the details of the samples nor the experimental procedure that was followed for the analyses. In a recent study, Basu *et al* (1993) have dated the Phenai Mata alkaline complex to 64.9 ± 0.11 Ma. Owing to its occurrence within the same alkaline district (Chhota Udaipur) of Deccan, Amba Dongar was also believed to have been emplaced close to Phenai Mata in time (Sen 1995; Simonetti *et al* 1998).

Earlier geochemical studies have not clearly established the genetic link between Amba Dongar with the surrounding Deccan tholeiites. Nevertheless, based on Wyllie (1988)'s model and the chronology of alkaline activities Basu *et al* (1993) have proposed that such alkaline activities either represent early or late igneous pulses of the Deccan flood basalt province. Based on combined Sr-Nd-Pb isotopic study on Amba Dongar carbonatites Simonetti *et al* (1995) suggested that these rocks bear signatures of a mantle plume and the similarity of various isotopic ratios with those of the least altered Deccan tholeiites has been interpreted by the authors as the evidence for the Reunion-Deccan plume derivation for Amba Dongar. According to Sen (1995), in a plume model the alkaline and carbonatite magmas are generated from the volatile rich rim of the plume, which is consistent with the observation that most of such complexes of Deccan occur in the periphery of the main tholeiitic eruptive center.

The relationship between the carbonatites and associated silicate rocks of Amba Dongar has not yet been established firmly. Some workers believe that these rocks were derived by means of silicate-carbonate melt immiscibility (Srivastava 1997; Ray 1997) and some believe that they have crystallized from two different parent magmas with the alkaline silicate being the older (Viladkar 1996). However, in a recent work of Sr isotope systematics in Amba Dongar and adjacent complexes (Ray 1998), it has been proposed that the silicate-carbonate melt immiscibility was responsible for their generation.

3. Experimental technique

Whole rock samples of alkaline silicates and phlogopite mineral separates from carbonatites were analyzed. For whole rocks, fresh samples were powdered in a stainless steel mortar and pestle to 100–150 μm size. About 600–700 mg aliquot of homogenized powders were used. For mineral separates (phlogopite), minerals were hand picked from whole rock powders and about 100–200 mg of pure mineral separates were taken for analysis. Whole rock powders and mineral separates were ultrasonicated with 0.05 N HCl (to remove unwanted carbonates) and water several times and dried before being packed for irradiation. The 520.4±1.7 Ma old Minnesota Hornblende (MMhb-1) (Samson and Alexander 1987) was used as a monitor. Samples along with the monitor were irradiated in the central core of the light water moderated APSARA reactor at the Bhabha Atomic Research Center, Mumbai, for about 100 hours. The reactor was not operative continuously, therefore, appropriate correction for ^{37}Ar decay was used (Venkatesan *et al* 1993). Maximum neutron fluence variation was estimated to be ~5%. Interference corrections were based on analysis of pure CaF_2 and K_2SO_4 salts irradiated with the samples. The values for $^{36}Ar/^{37}Ar$, $^{39}Ar/^{37}Ar$ and $^{40}Ar/^{39}Ar$ salt ratios are: 0.0003112, 0.0006827 and 0.079, respectively.

For each irradiated sample, argon gas was extracted in a series of fifteen or more steps of increasing temperatures up to 1400°C in an electrically heated ultra-high vacuum furnace. The isotopic ratios of the argon gas released in each step, after a two-step purification, was measured using an AEI MS10 mass spectrometer in static mode. We define a plateau as comprising four or more contiguous steps in an apparent age spectrum with apparent ages that overlap the mean at 2σ level of error excluding the error contribution from the J-value. The plateau ages are weighted means of the apparent ages of steps forming the plateaus. Weighted means of apparent ages are calculated using the method of Bevington (1969). Isochron ages have been computed using the two error regression method outlined by York (1969) of data points corresponding to the plateau steps.

4. Results and discussion

Three fresh alkaline rock samples (AD-16, AD-45 and AD-47) and a phlogopite separate from a carbonatite (AD-46) were dated (see figure 1 for sample locations). The plateau ages along with per cent ^{39}Ar included for the plateaus; isochron ages and inverse isochron ages of plateau steps along with ratios of trapped argon and MSWD values; and integrated (total) ages are summarized in table 1. The age spectra along with isotope correlation plots for all four samples are shown in figures 2–5. Errors quoted in all the values are at 2σ level. Two alkaline rocks (AD-16 and AD-45) and the phlogopite separate from a carbonatite (AD-46) yielded good plateaus in the age spectra (figures 2(a), 3(a) and 4(a)) giving ages of 64.8 ± 0.6 Ma, 64.7 ± 0.5 Ma, and 65.5 ± 0.8 Ma, respectively. The third alkaline rock (AD-47) yielded a 10 step high temperatures plateau (from 600°C to 1050°C) with an age of 65.3 ± 0.6 Ma (figure 5(a)). The three low temperature steps of AD-47 (figure 5(a)) showed higher apparent ages, perhaps due to recoil effect (Venkatesan *et al* 1993). The one or more initial and final temperature steps (figures 2(a), 3(a), 4(a) and 5(a)), which are not included in the plateaus, showed large errors in their apparent ages due to the very small amount of ^{39}Ar-release in these steps. For all the four samples, there is an excellent agreement between plateau and isochron ages indicating that these samples have not lost any significant amount of radiogenic argon since their crystallization. The undisturbed nature of these samples is also reflected in the total ages, which are indistinguishable from the plateau ages within the 2σ level of error. In the isotope correlation plots of the plateau steps of all these samples showed atmospheric trapped argon composition [i.e. $(^{40}Ar/^{36}Ar)_i = 295.5$] within the limits of uncertainties (2σ errors) implying that the plateau ages are the true ages of the samples. Indistinguishable ages of alkaline silicate rocks and carbonatites suggest that these two rock types of Amba Dongar complex are contemporaneous. Therefore, the weighted mean (determined following Bevington (1969)'s procedures) of all plateau ages, 65.0 ± 0.3 Ma, is the age of emplacement of the Amba Dongar complex.

The contemporaneity of alkaline silicate rocks and carbonatites of Amba Dongar complex is consistent with the idea of their formation as a result of carbonate-silicate liquid immiscibilty. The 65.0 ± 0.3 Ma age of this complex also suggests that the complex got emplaced towards the end phase of Deccan Trap magmatism and it is ~2.0 Ma younger than the main pulse of Deccan (67.0 Ma; Venkatesan *et al* 1993). As

Table 1. *Summary of results of ^{40}Ar-^{39}Ar dating of Amba Dongar samples.*

Sample	Plateau			Isochron			Inverse isochron			Integrated age
	steps	%^{39}Ar	Age (Ma)	Age (Ma)	Trap	MSWD	Age (Ma)	Trap	MSWD	
AD-16	13	97.88	64.8 ± 0.6	64.5 ± 1.7	297.4 ± 13.2	0.064	65.0 ± 4.3	292.7 ± 11.5	0.047	64.5 ± 1.5
AD-45	14	98.27	64.7 ± 0.5	65.0 ± 1.4	297.7 ± 12.8	0.282	64.5 ± 4.2	306.7 ± 13.2	0.069	65.5 ± 1.4
AD-46	10	98.27	65.5 ± 0.8	65.4 ± 1.9	295.9 ± 6.5	0.115	65.4 ± 3.3	295.9 ± 6.5	0.115	65.4 ± 1.6
AD-47	9	61.05	65.3 ± 0.6	65.4 ± 1.4	296.9 ± 23.4	0.116	65.0 ± 9.3	310.6 ± 29.9	0.059	67.2 ± 1.4

Note: Trap: Initial $^{40}Ar/^{36}Ar$ (trapped argon); MSWD: Mean Square Weighted Deviate.
Errors are 2σ.

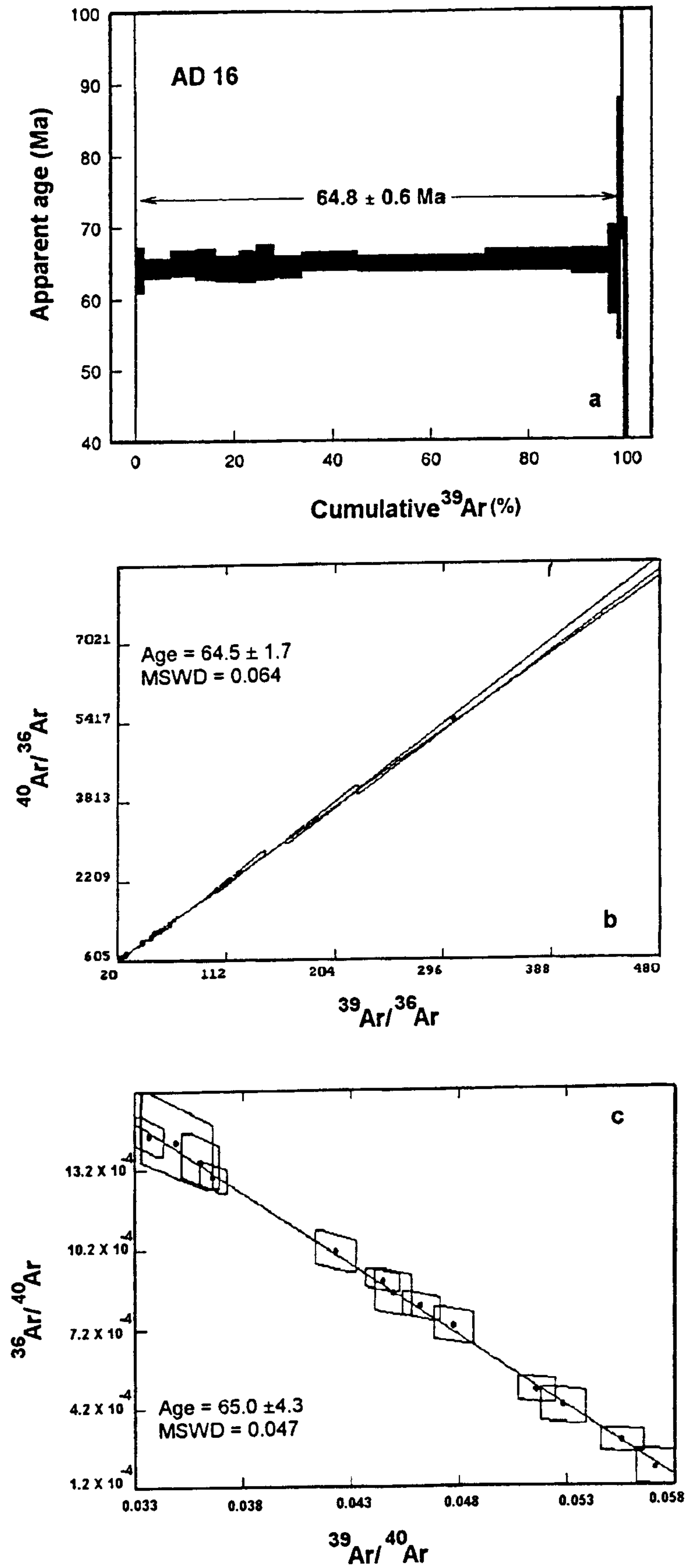

Figure 2. **(a)** Step heating ^{40}Ar-^{39}Ar apparent age spectrum for AD-16 (nephelinite). The age shown is the plateau age, which includes 2σ error on J but the vertical width of individual plateau boxes indicate 2σ errors calculated without error on J. **(b)** and **(c)** are isotope correlation diagrams (^{40}Ar/^{36}Ar vs. ^{39}Ar/^{36}Ar and ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isochron diagrams, respectively) for AD-16 showing 2σ error envelopes and regression lines.

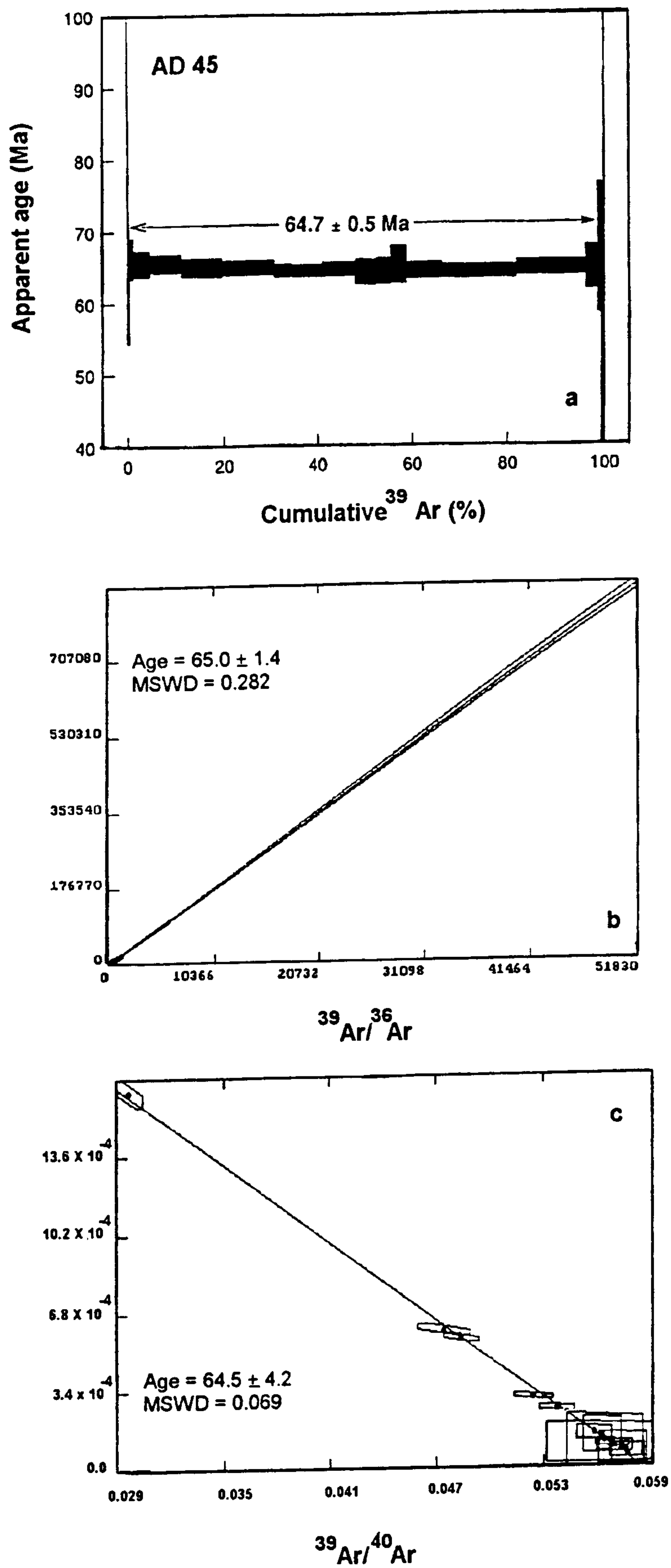

Figure 3. Step heating ^{40}Ar-^{39}Ar apparent age spectrum for AD-45 (tinguaite) **(a)** and isotope correlation diagrams **(b and c)**. Please also see the caption of figure 2.

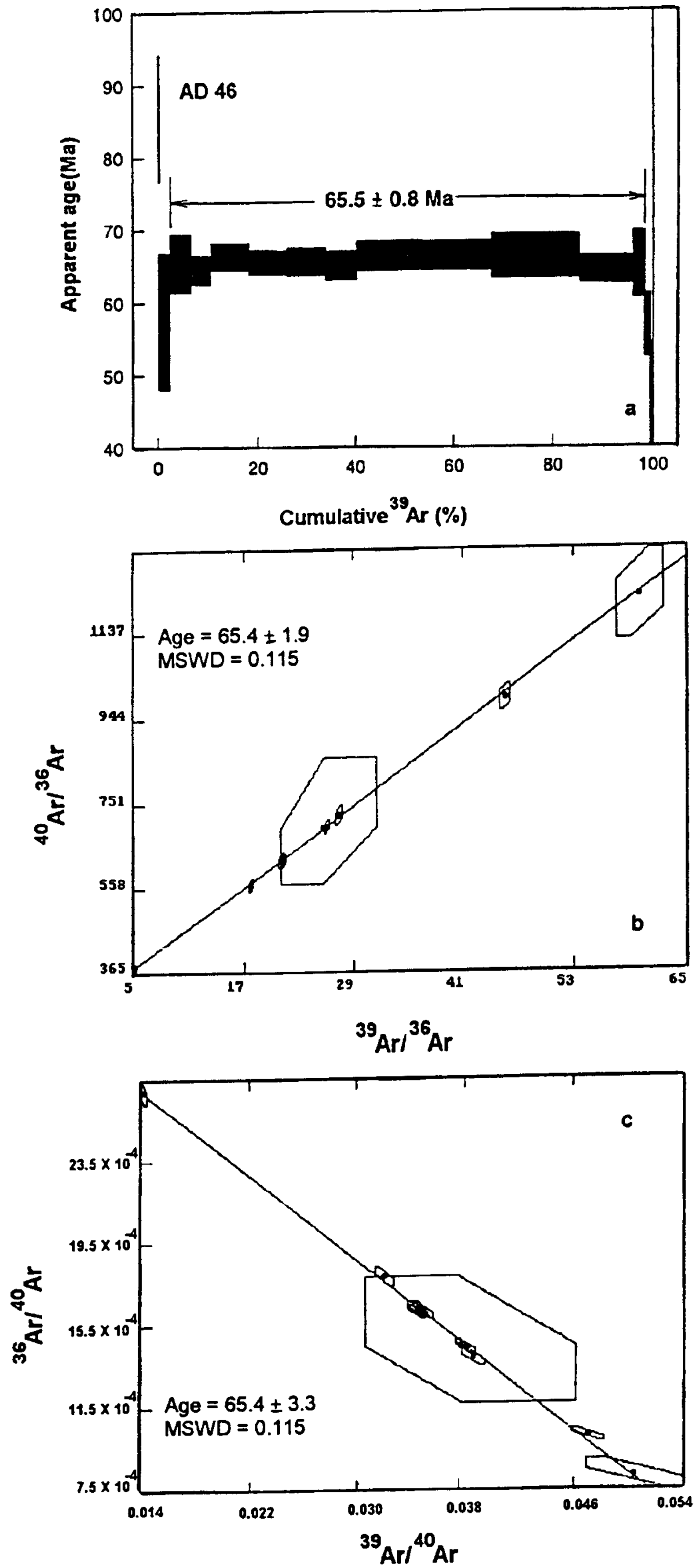

Figure 4. Step heating ^{40}Ar-^{39}Ar apparent age spectrum for AD-46 (phlogopite separate from a carbonatite) **(a)** and isotope correlation diagrams **(b and c)**. Please also see the caption of figure 2.

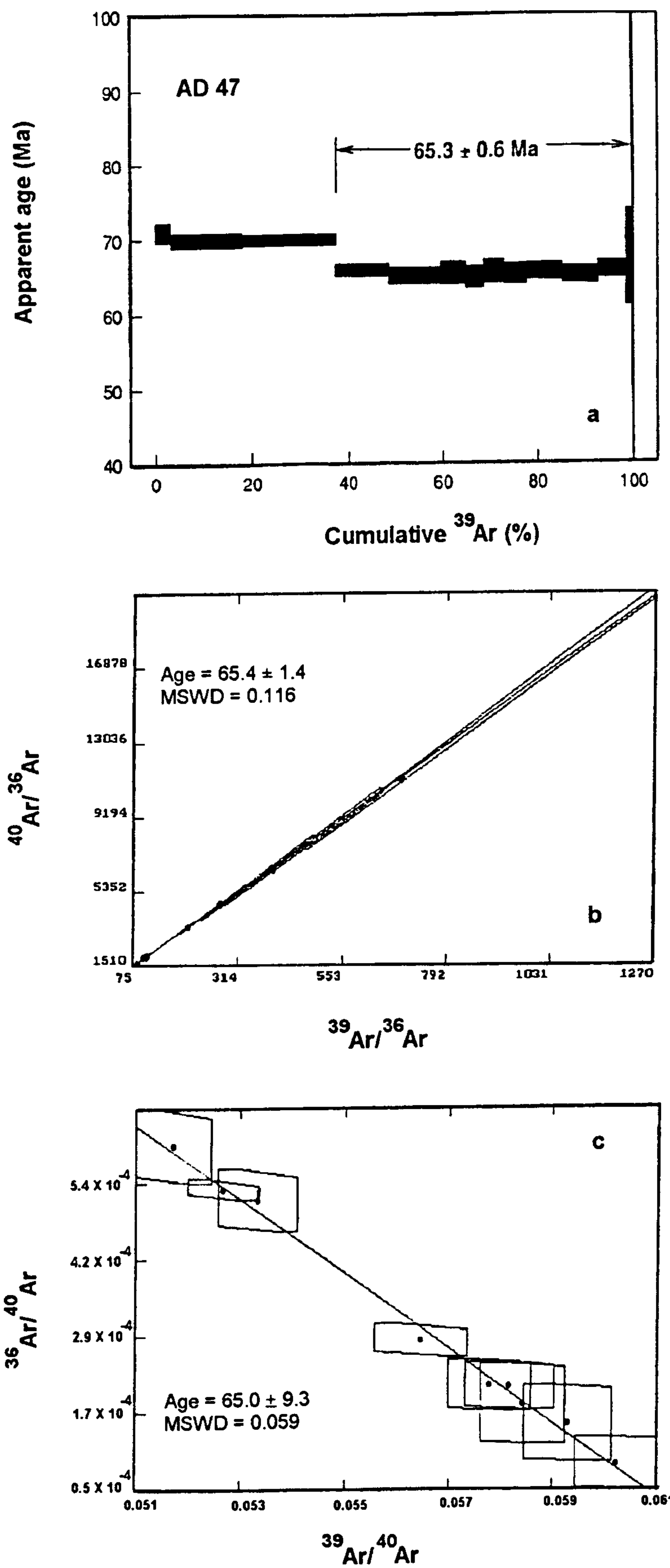

Figure 5. Step heating ^{40}Ar-^{39}Ar apparent age spectrum for AD-47 (tinguaite) **(a)** and isotope correlation diagrams **(b and c)**. Please also see the caption of figure 2.

mentioned earlier, the Amba Dongar complex intrudes into the Deccan tholeiites of this region. Therefore, the Traps of this region are older than 65.0 Ma. This age of Amba Dongar complex along with the two northern most 68.5 Ma old alkaline complexes at Sarnu-Dandali and Mundwara fits well in the plume theory for the generation of Deccan flood basalts and is consistent with the idea of 10–15 cm/year northward motion of the Indian plate over nascent Reunion hotspot (Basu *et al* 1993). In this plume model, Amba Dongar complex would represent a late stage alkaline magmatism on the northern end of the rim of the plume head at 65 Ma.

Amba Dongar is a part of the Chhota Udaipur carbonatite-alkaline district of Gujarat, which covers an area of $\sim 200\,km^2$ (Viladkar 1996) and consists of several alkaline complexes. Phenai Mata alkaline complex (present to the northwest of Amba Dongar), which is also a part of this district, has been dated to 64.96 ± 0.11 Ma by Basu *et al* (1993). This probably indicates that the carbonatite-alkaline magmatism of this district occurred at 65.0 Ma, which happens to be just at the K/T boundary (Izett *et al* 1991). This coincidence makes these carbonatite alkaline magmatisms very important in the ongoing debate on the K/T mass-extinctions. Alkaline and carbonatite magmatism are associated with the release of very high amount of $CO_2 + SO_2$ gases (Bailey and Hampton 1990). Owing to their very low viscosity and density (Treiman 1989) these melts get emplaced/erupted very fast (in a few years); (Williams *et al* 1986), which obviously results in a lot of volatile input into the atmosphere in a very short interval of time. A conservative estimation, using the procedures described by Leavitt (1982), shows that the total CO_2 flux from just the carbonatites of Chhota Udaipur district was 2.67×10^{14} moles, which came out in a very short period of time (in a few years). Workers who believe in the internal cause (i.e. Deccan Volcanism) to be responsible for the mass-extinctions at K/T boundary suggest that the high amount of CO_2 released due to the Deccan volcanism ($\sim 5 \times 10^{17}$ moles in ~ 1 Ma; McLean *et al* 1985) is one of the major reasons for the catastrophism. In this context the carbonatite-alkaline magmatism of Chhota Udaipur district would have enhanced the catastrophic effects due to addition of a very significant amount of CO_2 in a very short time into the already disturbed atmosphere. A similar estimation for SO_2 released during these activities is in progress.

5. Conclusion

The age of Amba Dongar carbonatite-alkaline complex is 65 Ma. This age implies that the complex got emplaced late in the Deccan flood basalt volcanism and is consistent with the Reunion-Deccan plume hypothesis proposed for the origin of this complex. This complex appears to be coeval with many other alkaline complexes of Chhota Udaipur subprovince of the Narmada region. Being emplaced just at the K/T boundary these could have enhanced the catastrophic effects leading to mass extinctions, by rapidly injecting a substantial amount of CO_2 and probably SO_2 as well into the atmosphere.

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