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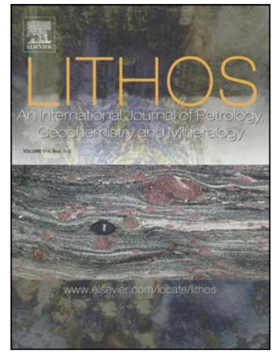

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Post-K/PB younger ^{40}Ar - ^{39}Ar ages of the Mandla lavas: Implications for the duration of the Deccan volcanism

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ABSTRACT:

We present new age determinations, derived from ^{40}Ar-^{39}Ar incremental heating experiments, for basaltic lava flows from the Mandla lobe, located on the eastern margin of the main Deccan volcanic province, some ~ 1000 km from the Western Ghats escarpment. The most reliable estimates of crystallization ages come from 5 plateau ages from plagioclase separates, from a stratigraphically controlled succession of 37 lava flows. We detect no statistically significant age difference from bottom to top (range 63-65 Ma) and calculate a weighted mean age for the section at 64.21 +/- 0.33 Ma. These lava flows are significantly younger than the majority of the main Deccan volcanic activity documented from the Western Ghats (67-65 Ma). The new ages are consistent, however, with geochemical correlation of the Mandla lobe lavas with the uppermost succession (Poladpur-Ambenali-Mahabaleshwar Formations) of the SW Deccan, and indicate that this post K/PB youngest phase of flood basalt activity erupted over much of the province.

Keywords: K/PB, ^{40}Ar-^{39}Ar dating, Deccan volcanism, Mandla lavas

1. Introduction

Eroded remnants of the Deccan Traps (Fig. 1) outcrop in India over an eruptive area of 0.51 x 10^6 $km^2$and represent a continental flood basalt province that records immense accumulations of tholeiitic basalt in a relatively short period (perhaps largely completed in about 0.5 m.y.; Courtillot, 1990) straddling the Cretaceous-Paleocene boundary (K/PB, age ca. 66.0 Ma; Gradstein et al., 2012). Recent studies (Paul et al., 2013; Schoene et al., 2014) conclude that the Deccan volcanic activity initiated prior to the K/PB, however, with the main episode of volcanic activity occurring ~ 300 k.y. earlier than or at the K/PB itself. An early pulse of the volcanism occurred near the C30r/C30n transition (Pande, 2002), followed by two megapulses around 66 ± 1Ma, one entirely within C29r just before the K/PB, and the other shortly afterward

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spanning the C29r/C29n reversal - a total period of approximately 2.5 Ma (Chenet et al., 2007). Recent studies on the duration of Deccan volcanism further suggest that the main eruptive event took place in <1 m.y., spanning the K/PB mass extinction. An earlier episode of volcanism occurred 67-68 Ma (Keller et al., 2008). Models of upper mantle thermal regime and melting (Richards et al., 1989), mantle plume-lithosphere interaction (White and McKenzie, 1995) and environmental impacts of degassing during eruptions in large igneous provinces (Coffin et al., 2006), and the Deccan flood basalts in particular (Chenet et al., 2009), are very dependent on the detailed history of eruption volumes and frequency. It now appears that the main accumulation of Deccan lava flows formed in a series of gigantic and rapid eruptive events with individual duration of decades (Chenet et al., 2007, 2008), separated by ~10^4 year periods of quiescence. However, determination of the duration of episodes of volcanic activity, volumes of erupted material, and length of quiescent intervals is still not fully known.

The Deccan volcanic province is one of the largest igneous provinces in the world, where a wealth of data is available on its stratigraphy, structure, geochemistry, petrogenesis, and the age and duration of volcanism. The thickest accumulation of basaltic lava flows in the Western Ghats is stratigraphically controlled and geochemically well characterized (Pattanayak and Shrivastava, 1999: Cited Figure: Fig.1 and references therein; Shrivastava, et al., 2014). The stratigraphic framework of the Western Ghats region is known from detailed field, chemical, isotopic and palaeomagnetic studies (Cox and Hawkesworth, 1985; Beane et al., 1986; Lightfoot and Hawkesworth, 1988; Mahoney, 1988; Subbarao, 1988a; Subbarao, 1988b; Lightfoot et al., 1990; Peng et al., 1994; Vandamme and Courtillot, 1992) and correlated with thinner sections of lava flows preserved in other areas (Deshmukh et al., 1996; Sheth et al., 1997; Peng et al., 1998;

Chandrasekharam et al., 1998, 1999, 2000; Mahoney et al., 2000; Melluso et al., 2006; Self et al., 2008; Chatterjee and Bhattacharji, 2008; Sethna and Gwalani, 2011; Vanderkluysen et al., 2011).

In this paper we follow the time scale of Gradstein et al. (2012), which is calibrated against recent revisions of the age of standard minerals and decay and abundance constants used in ^{40}Ar-^{39}Ar dating (Min et al., 2000; Kuiper et al., 2008). For comparison with our new age determinations we have recalculated previously reported ages using the recommended calibration. Published age data place the entire sequence of Deccan lava flows between 60-67 Ma (Duncan and Pyle, 1988; Courtillot et al., 1988; Jaegar et al., 1989; Vandamme et al., 1991; Widdowson et al., 2000), although K-Ar ages as well as ^{40}Ar-^{39}Ar ages as high as 80 Ma and as low as 40 Ma have also been reported from the Deccan by earlier workers (Rama, 1968; Agrawal and Rama, 1971; Kaneoka and Haramura, 1973; Kaneoka, 1980; Alexander, 1981).The palaeontological data, particularly the remains of the ray *Igdabatis* from the Lameta beds, near Jabalpur by H. Cappetta (in Courtillot et al., 1986) indicate that the Deccan volcanism started in the Maastrichtian, after 72 Ma, possibly in the *Abathomphalusmayaroensis* zone around 68 Ma, and ended probably before 61 Ma (Vandamme et al., 1991). These constraints imply that the suggestions of major eruptive phases before 75 Ma (Alexander, 1981; Rao et al., 1985) and after 60 Ma (Pal, 1969; Pal and Bhimashankaram, 1971; Alexander, 1981) are incorrect and prompted Vandamme et al. (1991) to propose that Deccan volcanism lasted for a shorter period (about 5 m.y.) as suspected by McElhinny (1968).

The small number of geomagnetic field reversals found in the Deccan Traps is compatible with the idea that most of the volcanic activity occurred within a ~1 m.y. period, straddling the K/PB in the Chron 29r (Courtillot et al., 1986; Gallet et al.,1989; Jaegar et al., 1989).With the concept of "a short duration of major eruption in Deccan province", Vandamme et al. (1991) opined that the K-Ar age histogram should be interpreted in terms of a convolution between a narrow true age distribution and a "filter" characterizing alteration and argon loss. Jaegar et al. (1989) pointed out that the overall mean of the best ^{40}Ar-^{39}Ar ages of the Deccan may yield one of the best estimates of the K/PB age. They calculated this age to be 65.7±2.0 Ma, which Vandamme et al. (1991) adjusted to65.5±2.5Ma. Venkatesan et al. (1993) have proposed that the time interval between the reversely magnetized voluminous eruptions of the main sequence and the K/PB is not less than 1.5 m.y. Baksi (1994) integrated age data with magnetic polarity of lava formations in the western Deccan and concluded that >80% of the exposed material was erupted in ~1 m.y., bracketing Chron 29r.However, he suspected an undetected Ar loss of ~3% would shift the whole-rock basalt and the plagioclase crystallization ages to ~68 Ma, indicating that the bulk of the Deccan lava flows were erupted in Chron 31r.Venkatesan et al. (1993) have noted the “difficulties of assessing the amount of eroded material, the volume of basalt below the surface and in the offshore extrusions of the Deccan province and finally due to the aerial extent of individual flows."

Salil et al. (1996, 1997) remarked on mineralogical and chemical similarities between smectite-dominant detrital clays of the Lameta beds and the weathered Deccan basalt, which pointed to the availability of Deccan lava flows at the time of Maastrichtian Lameta sedimentation. Of late, Shrivastava et al. (2012) have observed that the clay minerals associated with intra-volcanic bole horizons represent a high order of structural and compositional maturity, suggesting a significant hiatus between the volcanic episodes. This is in contrast to the model of an extremely short period of main Deccan volcanism of ~0.5 m.y. at the K/PB (Courtillot, 1990), but supports the model of a prolonged duration of Deccan volcanism (Basu et al., 1993;

Venkatesan et al., 1993; Baksi, 1994), with perhaps several intense volcanic episodes and long periods of inactivity between them (Chenet et al., 2008, 2009).

The isolated location and great thickness (~900 m) of the lava flow section that occurs around Mandla in the eastern periphery presents a significant unresolved fragment of the Deccan volcanic province (Fig. 1). Barring a few whole rock ages (e. g. 66.5±0.3 and 65.9±0.3 Ma) for Chakhla-Delakhari sill (Sen and Cohen, 1994) from the western periphery of this outlier, ^{40}Ar-^{39}Ar dates are not available for these lava flows. Therefore, for better understanding of the relationship of these isolated lava flows, located ~1000 km east of the main stratigraphic succession in the Western Ghats, we undertook ^{40}Ar-^{39}Ar age determinations to correlate these lava flows with the main section to the west and to further document the full eruptive history of Deccan volcanism.

2. Field study and sampling

Basalts of the Mandla lobe outcrop over an area of 29,400 km^2 in a thick pile of lava flows, preserved as an isolated remnant of erosion on the eastern extremity of the Deccan Traps (Fig. 2). Combined field, petrographic and major-elemental studies (Pattanayak and Shrivastava, 1996a, b; Pattanayak and Shrivastava, 1999; Shrivastava and Pattanayak, S.K., 2002; Shrivastava and Ahmad, 2005; Shrivastava et al., 2014) have resolved that this lobe is comprised of 37 lava flows. It extends 344 km in the E-W and 156 km in the N-S directions around Seoni, Jabalpur, Mandla, Dindori and Amarkantak areas (Fig. 2). The landscape is covered by flat-topped plateaus (Maikala) and ridges that often form small mesas and buttes. The contact between the base of the Traps and underlying sedimentary Lameta beds is at 364 m above mean sea level near Jabalpur and the maximum elevation of the lava flow sequence is 1177 m at Badargarh Mountain near Amarkantak. Overall, the lava pile attains a thickness of ~900 m and major topographic breaks occur at elevations of about 450, 600 and 900 m (Fig. 2ii). Duricrusts of laterite often cap the plateau above these breaks. Several cascades and gorges in the westward-draining River Narmada near Amarkantak, Dindori, Mandla and Jabalpur areas provide stratigraphically important lava flow exposures.

On the basis of reconnaissance surveys, three traverses (Fig.2ii), depicted as A-B (Rukher- Sivni), B-C (Sivni-Amarkantak) and D-E (Nainpur- Shahpura), were designed to obtain a flow-stratigraphic resolution of the complete section. Most of the lava sections were measured and verified using contour lines on the topographic sheets (Scale = 1:50,000).

3. Analytical procedure, accuracy and precision of analysis

The samples selected for age determinations were judged to be the freshest, best crystallized and least weathered, on the basis of thin section examination. Eight such samples come from the entire range of 37 lava flows that make up the composite Mandla lobe section (Shrivatava and Ahmad, 2005). Based on combinations of trace elements (Ba, Ti, Zr, Rb, Sr) and the Nb/Zr values, Shrivastava et al. (2014) have grouped these 37 lava flows, numbered from base to top, into six chemical types that are separated stratigraphically. Sample MK2 is from Flow 1, a fine-grained sparsely plagioclase-phyric tholeiitic basalt; MK6 and NL F2/S2 are separate samples from Flow 4, a plagioclase-phyric, high-alumina tholeiitic basalt; LC F1/S1 is from Flow 11, a plagioclase-phyric, columnar high-alumina tholeiitic basalt; KWR F4/S4 is from Flow 23, a coarse-grained tholeiitic basalt; BG F5/S5 is from Flow 27, a plagioclase-phyric, high-alumina tholeiitic basalt; SK F10/S10 is from Flow 31, a sparsely plagioclase- and olivine-phyric tholeiitic basalt; and PLB F12/S12 is from Flow 37, a plagioclase-phyric, high-alumina tholeiitic basalt.

We prepared samples for radiometric dating by crushing and sieving to obtain the 0.1-0.5 mm size fraction. We then separated plagioclase from samples MK2, MK6, NL F2/S2, SK F10/S10 and PLB F12/S12 with a Frantz magnetic separator. We retained the whole rock crushed fractions from samples LC F1/S1, KWR F4/S4 and BG F5/S5, for which feldspar was more altered along cleavage to clay minerals. All samples were ultrasonically washed in nitric and hydrochloric acid solutions, then deionized water, and dried. We monitored the potential impact of Cl on ^{36}Ar production by measuring ^{38}Ar, and found no significant contamination. Plagioclase separates were cleaned briefly in a weak hydrofluoric acid solution to remove altered grain margins and cleavage surfaces. Finally, we hand-picked the plagioclase separates and whole rock fractions to obtain clean aliquots for analyses. We wrapped the prepared samples in Cu-foil, and loaded them in evaluated quartz tubes for irradiation in the TRIGA experimental nuclear reactor at Oregon State University. Samples sat near the central core of the reactor for 6 hr at 1 MW power, which we monitored with FCT-3 biotite (28.201 Ma, Kuiper et al., 2008). After cooling, we loaded the irradiated samples into an all-metal, gas extraction line, with a chamber fitted with a BaF window. We heated each sample with a 10W CO_2 continuous power laser, in 10-12 temperature steps from 400°C to fusion. Gas released at each step passed over several sets of Zr-Al getters before analysis of Ar-isotopic composition (masses 36, 37, 38, 39 and 40) with a MAP 215/50 mass spectrometer, fitted with an ion multiplier. Further details of analytical procedures are described in Storey et al. (2007).

We calculated sample ages using the ArArCALC software (Koppers, 2002) using the corrected Steiger and Jager (1977) decay constant of 5.53 ± 0.097 x 10^{-10} yr^{-1} (2σ) as reported by Min et al. (2000). The redetermined Ar-isotopic atmospheric composition (Lee et al., 2006) does not have a significant effect on calculated ages, compared to Nier (1950) value, and all previously reported Deccan age data used the traditional value, so we did likewise. Age spectra were examined for contiguous, concordant heating step ages comprising at least 50% of the gas released. Plateau ages are the weighted mean (by inverse variance) of five or more such concordant temperature steps and represent between 92 and 100% of the total ^{39}Ar released (Fig. 3). Generally, these are simple age spectra with clear middle and high temperature plateaus and commonly exhibit Ar-loss low temperature steps. Isochron ages, calculated from the slope of linear regressions of $^{40}Ar/^{36}Ar$ vs $^{39}Ar/^{36}Ar$ ("normal") and $^{36}Ar/^{40}Ar$ vs $^{39}Ar/^{40}Ar$ ("inverse") step compositions, agree with the plateau ages and initial $^{40}Ar/^{36}Ar$ ratios are within error of the atmospheric value (295.5). The flux gradient factor, J, was calculated by fitting a second-order polynomial to measured values at 7 positions (two measurements each) along the irradiated vials, and interpolating for sample position. Ages are reported with 2σ analytical errors that include uncertainties in J. In view of evidence that the biotite (FCT-3) is measurably older than sanidine (FCs) in the Fish Canyon Tuff from which the Kuiper et al. (2008) age is determined, we have used the intercalibration factor 1.005 provided by Daze et al. (2003) to adjust our calculated agesfrom those calibrated against FCT-3 biotite (Appendix 1) to those summarized in Table 1 and Figure 3 (FCs sanidine).

4. Results

Analytical results are presented in Table 1, with total fusion, plateau and normal isochron ages, and initial $^{40}Ar/^{36}Ar$, each with analytical errors quoted at 2σ level. MSWD is an F-statistic that compares the variance within step ages with the variance about the plateau age. Values less than about 2 indicate that the step ages that comprise the plateau all come from the same population and that the plateau age is acceptable from a statistical perspective. We note that selection of heating step ages to include in plateau and isochron ages is somewhat subjective, although we are guided by the desire to include as many concordant steps as possible without exceeding statistically significant MSWD values. The age spectra, normal and inverse isochron plots are presented in Figure 3. An additional plot, K/Ca vs cumulative ^{39}Ar released (Fig. 3), comes from measurements of $^{39}Ar/^{37}Ar$ and is useful in deciphering the composition of phase(s) contributing to the release of Ar with increasing temperature in the whole rock heating experiments.

Sample PLB F12S12 plagioclase (Fig. 3: ai- aiv) has a 9-step (96% of total gas released) plateau age of 64.08±0.51 Ma. Its normal isochron age is 64.01±0.87Ma, indistinguishable from its plateau age, and its inverse isochron age is 64.23±0.85 Ma, which is again consistent with its plateau age. The mean square of weighted deviates (MSWD) on the plateau age is 0.97, and the $^{40}Ar/^{36}Ar$ intercept is close to the atmospheric value. The K/Ca plot indicates a uniform composition, high-Ca plagioclase as the source of Ar throughout the temperature range. Sample SK F10S10 plagioclase (Fig. 3: bi- biv) has an 8-step (100% of total gas released) plateau age of 64.41±0.65 Ma. Its isochron age is 64.45±1.23 Ma, and the MSWD value for the plateau age is 0.12. The measured $^{40}Ar/^{36}Ar$ intercept value is also atmospheric. The inverse isochron age is 64.46±1.23 Ma. The K/Ca plot is consistent with a single phase (high Ca plagioclase).

Sample BG F5S5 whole rock yields an age of 47.74±0.53 Ma, from 5 of 11 heating steps comprising a little over 50% of the total gas released (Fig. 3: ci- civ). The age spectrum shows clear evidence of Ar-loss in the first 5 steps, and it is likely that diffusive loss has affected the whole sample. The normal and inverse isochron ages, based on the same plateau-defining step compositions, are concordant with the plateau age, which we consider to be aminimum age estimate. The K/Ca plot indicates considerable variation in the composition of phases contributing to Ar release with increasing temperature, from relatively K-rich (clays, groundmass) at low temperatures to K-poor (plagioclase, pyroxene) at high temperatures. Whole rock sample KWR F4S4 (Fig. 3: di- div) produced an age of 60.60±0.61 Ma from 8of 11 heating steps (94% of the total gas released). This age spectrum shows less Ar-loss, and an acceptable MSWD at 0.81. The normal as well as inverse isochron ages are compatible with the plateau age, and the $^{40}Ar/^{36}Ar$ intercept is within analytical error of the atmospheric value. Sample LC F1S1 whole rock (Fig. 3: ei- eiv) produced an age of 61.38±0.42 Ma from 8 of 13 steps; however the quasi-plateau comprises less than 50% of the gas released, and there is clear evidence for Ar-loss in the low temperature (majority) steps of the spectrum. On this basis we consider the plateau to provide a minimum age only. The normal and inverse isochron ages are compatible with the plateau age and the $^{40}Ar/^{36}Ar$ intercept (289±19) is within uncertainty of the atmospheric value. The K/Ca spectrum indicates release of Ar from K-rich sites (clays, groundmass) at low temperatures and K-poor sites (plagioclase, pyroxene) at high temperatures.

Sample NL F2S2 plagioclase (Fig. 3: fi- fiv) produced a plateau age of 63.99±1.21 Ma, from 8 of 10 heating steps (92% of the total gas released). The normal isochron age of this sample is 60.69±3.74 Ma, and the $^{40}Ar/^{36}Ar$ intercept is atmospheric. The inverse isochron age is 60.76±3.70 Ma; both isochron ages are younger than but within analytical uncertainty of the more precise plateau age. The K/Ca plot is consistent with uniform Ar release from a high-Ca plagioclase. Sample MK6 plagioclase (Fig.3: gi- giv) provided a plateau age of 65.18±1.22 Ma, from 8 of 8 heating steps (100% of the total gas released). The normal and inverse isochron ages are concordant with the plateau age, the $^{40}Ar/^{36}Ar$ intercept is atmospheric, and the K/Ca spectrum clearly shows the contribution of a single high-Ca feldspar phase. Sample MK2 plagioclase (Fig.3: hi- hiv) produced a plateau age of 63.51±1.15 Ma from 7 of 8 steps (98% of the total gas released). The normal and inverse isochron ages are consistent with the plateau age, and the $^{40}Ar/^{36}Ar$ intercept is within analytical error of the atmospheric value. The K/Ca plot is again consistent with gas release from a high-Ca feldspar.

The age data for 5 of the 8 analyzed samples (plagioclase separates PLB F12/S12, SK F10/S10, NL F2/S2, MK6 and MK2) are easily interpreted as reliable crystallization ages, based on extensive plateaus (92-100% of gas released), concordant isochron ages and atmospheric values of initial $^{40}Ar/^{36}Ar$. Whole rock samples BG F5/S5, KWR F4/S4 and LC F1/S1 show less convincing plateaus (44-94% of total gas released) and clear Ar-loss at low temperature steps. The plateau ages derived from these three samples are significantly younger than the 5 ages calculated from plagioclase separates. In addition, the ages (~48-61 Ma) are significantly younger than the lava flows above and below them, so from a geological perspective these ages are suspect. We accept the plateau ages from the 5 plagioclase separates as the best estimate of the age of the Mandla lobe lava flow sequence, 63-65 Ma. Since there is no significant age difference between the bottom and top of the lava flow section (Flow 1 to Flow 37), we calculate a weighted mean age for the entire section of 64.21±0.33 Ma.

5.Discussion

Widdowson et al. (2000) report geochemical data from basaltic dykes in the Goa region, southwestern Deccan, that have the characteristics of the closest lava flows immediately to the north. These belong to the Ambenali, Mahabaleshwar and Panhala Formations (of the Wai Subgroup), which are upper most in the Deccan volcanic stratigraphy (Fig. 4; Beane et al., 1986; Subbarao et al., 1988a). These authors also provide whole rock ^{40}Ar-^{39}Ar age determinations on four of the dykes that exhibit age spectra affected by “excess ^{40}Ar” (mantle-derived, incompletely equilibrated with atmospheric Ar at the time of crystallization). Plateau ages of 64-65 Ma (re-calculated to monitor FCs age at 28.201 Ma) are derived from only 35-50% of the total gas released. These ages are corroborated, however, by concordant isochrons with initial $^{40}Ar/^{36}Ar$ compositions close theatmospheric value. In view of the evidence for excess ^{40}Ar, these are considered maximum ages.

Venkatesan et al. (1993) determined ages of 63-64 Ma for two samples from the Mahabaleshwar-lowermost Panhala Formations. A similarly young age for the uppermost, SW Deccan lava flows was provided by Duncan and Pringle (1991). Chenet et al. (2007) find a mean age of 64.9±0.6 Ma for 4 determinations from the topmost (Ambenali-Mahabaleshwar) formations. Knight et al. (2003) dated the Rajahmundry lava flows, located on the SE coast of India ~900 km from the Western Ghats, at 65.1±0.5 Ma (mean of 8 plateau ages from plagioclase separates). These lavas bracket the C29r-C29n boundary and are best correlated geochemically with Ambenali-Mahabaleshwar lava compositions (Self et al., 2008).Chemostratigraphic mapping of the Deccan province has shown that the uppermost formations (i.e., Panhala, Mahabaleshwar,Ambenali and Poladpur) are particularly widespread, and not restricted to the SW Deccan (Mitchell and Widdowson, 1991; Bilgrami, 1999; Peng and Mahoney, 1995; Peng et al., 1998; Mahoney et al., 2000; Subbarao et al., 1994). Widdowson et al. (2000) assert that these Wai Subgroup lava flows "represent the most widespread and volumetrically significant episode of Deccan eruptive history. Mandla lavas show general chemical affinities to the Poladpur and Ambenali formations (Shrivastava et al., 2014) as reported earlier in the reconnaissance work by Peng et al. (1998). In addition, several flows of this area are also similar to those of the Mahabaleshwar Formation. Based on isotopic and trace element data, the superposition of Mahabaleshwar-like flows over flows with Ambenali- and Poladpur-like characteristics is in the same stratigraphic order as seen in the southwestern Deccan type-section.

Our results contribute to our understanding of the total duration of Deccan volcanism, and the large extent of these younger lava flows. The new ages confirm that the uppermost lava flow formations (of the Wai subgroup) extended over large areas of central India at least until 63 Ma. This qualifies the concept of short duration (~1 m.y.) suggested by Courtillot et al. (1986; 1988), Duncan and Pyle (1988) and Allegreet al. (1999) for the main Deccan volcanic province. We conclude that the Mandla lobe sequence of lava flows is younger than the main Deccan lava flow sequence in the Western Ghats, by 1 to 1.5 m.y. Thus, the outpouring of lavas in the eastern margin of the Deccan province started after the main episode of volcanism in western sequence; i.e., about 65 Ma and continued for a short period, perhaps until ~63 Ma (Fig. 4). The thicknesses of lava flow sections (Poladpur-Mahabaleshwar-Ambenali formations) seen in the Western Ghats and Mandla lobe areas are similar (~1000m); however the greater occurrence of dykes in the former indicates closer proximity to the source of eruptions (plume). Hence, lava flows traveled great distances (up to 1000 km) from the Western Ghats area to accumulate in the Mandla lobe area. This could have occurred through flow inflation and lava tubes (Hon et al., 1994) or as intracanyon flows (Baksi et al., 1994).

Palaeomagnetic studies of Vandamme and Courtillot (1992) on lava flows near Jabalpur, Kundam and Lakhnadon (in the Mandla lobe outcrop) reconcile the entire data-set with the proposed 30n-29r-29n reversal sequence for the well-established magnetostratigraphy of the western Deccan (Vandamme et al., 1991). The geologic time-scale of Gradstein et al. (2012) assigns ages of ~68.2-66.4, ~66.4-65.7 and ~65.7-65.0 Ma to chrons 30n, 29r and 29n, respectively (Fig. 4). Lava flows with normal polarity were reported from the Mandla area (Schöbel, et al., 2014) and assigned to Chron 30n. This follows Vandamme (1991) who determined normal polarity of lava flows from Seoni and Jabalpur areas at the base of the sequence where the 4th lava flow of Pattanayak and Shrivastava (1999) and Shrivastava et al. (2014) occurs. It marks the beginning of the volcanic activity in this area. From these geomagnetic polarity time scale assignments Schöbel et al. (2014) estimated a duration for these flows as 0.7 Ma(minimal C30n, C29r: 0.7 Ma) to 2.3 Ma (maximal C30n:1.6 Ma; C29r: 0.7 Ma). Our new ages indicate that these lava flows are significantly younger than these previous estimates based on magnetic polarity alone, and are better assigned to the C29n-C28r-C28n sequence, which is 63.5-65.7 Ma inclusive, and could be much shorter (Fig. 4).

Boles are well-preserved weathered profiles or palaeosols, the product of *"in-situ"* weathering of flow tops that developed in the time interval between two successive lava flows. On the basis of structural and compositional maturity of bole clays from more than 21 bole horizons of different thicknesses that occur across the eastern Deccan volcanic succession, Shrivastava et el. (2012) argue that a period of greater than 5.34 Ma is necessary for their formation. (From limited paleosecular variation, however, Chenet et al., 2008, propose that boles form over much shorter intervals – perhaps ~10^4 yr.) Moreover, Late Maastrichtian Lameta beds (sediments underlying and fringing the *visibly lowermost* lava flows in the eastern Deccan volcanic province)record evidence of detrital input from Deccan volcanism (Salil et al., 1994, 1996a, 1996b and 1997) beginning as early as 70 Ma. Considering time implications of formation of bole clays (Shrivastava et al., 2012), it is possible that the volcanic activity started in the Late Maastrichtian and continued through peak activity around 65 Ma, to waning activity much later, thus supporting a model of longer total duration of Deccan volcanism. It is also consistent with the geomagnetic polarity boundaries (Fig. 4) of Gradstein et al. (2012). Chenet et al. (2007) report a mean (N = 7) age of 65.1±0.5 Ma for the main Deccan phase of activity (Fig. 4) from K-Ar analyses using the 'unspiked' Cassignol-Gillot method, while Hoffman et al.

(2000) find a mean (N = 5) age of 66.2±0.4 Ma for lava flows from the lower section (Jawhar and Igatpuri) formations consistent with the K/PB age of 66.0 Ma (Gradstein et al, 2012). Deccan volcanic activity started earlier than the K/PB, but a major episode of volcanism occurred either ~300 ky before the K/PB or at the K/PB itself (Paul et al., 2013).Sedimentologic, microfacies and biostratigraphic studies of Keller et al. (2008) on intertrappean sediments at the Rajahmundry Traps concluded that the deposition of these sediments occurred in the Early Danian Zone (Pla), within C29r but ~200 ky above the K/PB boundary.

6. Conclusions

The most reliable estimates of crystallization ages from plagioclase separates from a stratigraphically controlled succession of 37 lava flows from the Mandla lobe indicate no statistically significant age difference from bottom to top (range 63-65 Ma) and we calculate a weighted mean age for the section is 64.21±0.33 Ma. Thus, these post-K/PB lava flows in this region are significantly younger than the majority of the main Deccan volcanic activity documented from the Western Ghats (67-65 Ma). The new ages are consistent, however, with geochemical correlation of the Mandla lobe lavas with the uppermost succession Ambenali-Mahabaleshwar Formations) of the SW Deccan, and indicate that this post-K/PB youngest phase of flood basalt activity erupted over much of the province (Fig. 4). The Late Maastrichtian Lameta beds date initial Deccan volcanism (Salil et al., 1994, 1996a, 1996b and 1997) to as early as 70 Ma and considering the estimated time of formation of bole clays (>5 Ma), it appears that the volcanic activity started earlier in the Late Maastrichtian, then continued through peak eruption rates ~66 Ma to at least 63 Ma, thus supporting a model of an extended duration of Deccan volcanism. The total duration of volcanic eruption in eastern Deccan volcanic province is at least 7 m.y. and encompasses the K/PB. It is probable that after the peak activity in the western Deccan volcanic province, eruptions continued in the east, although at more modest eruption rates (Kashyap et al., 2010). We conclude that the Deccan volcanism occurred in several phases – an earlier phase formed the great western succession of lava flows, whereas, the later phase formed the terminal lava flows of the southwest region and the entire succession of the Mandla lobe in the east.

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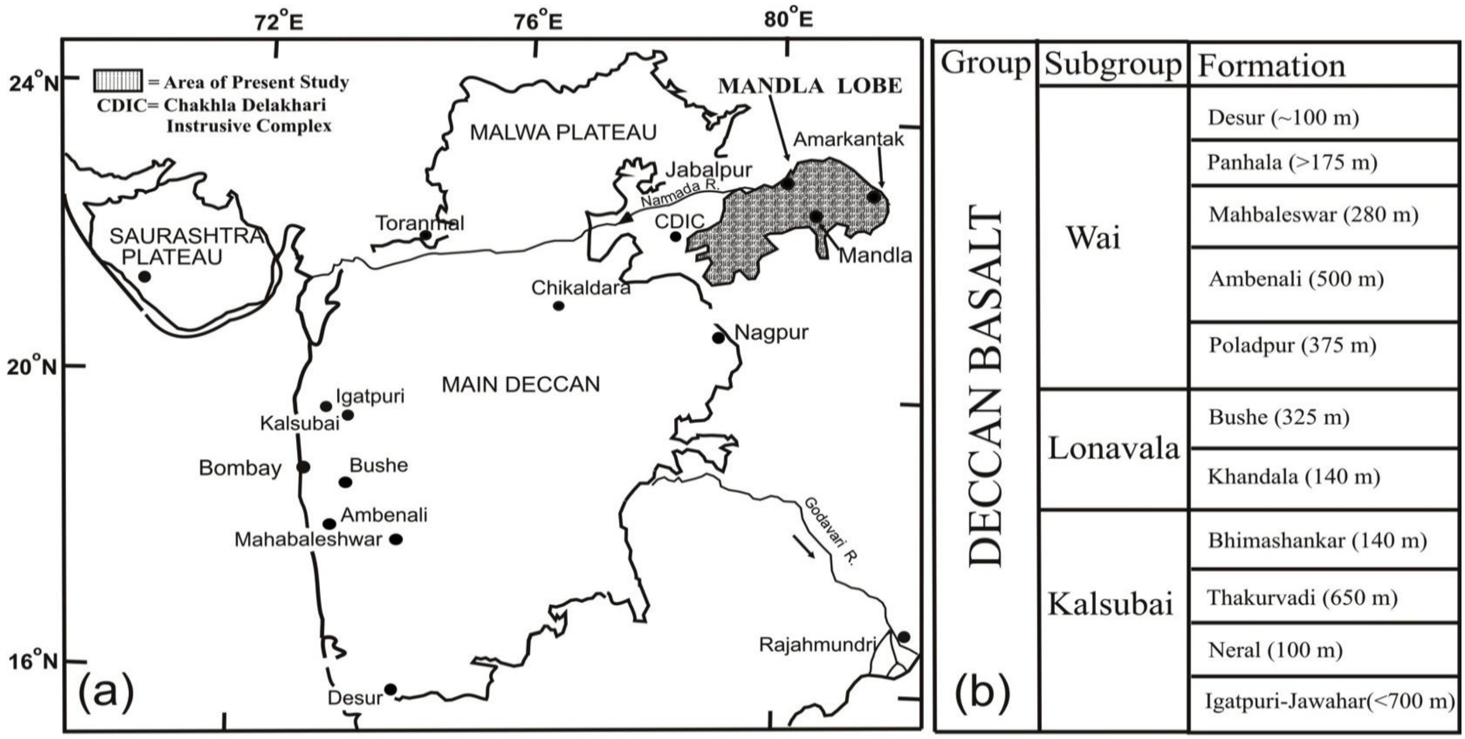
Table 1. ^{40}Ar-^{39}Ar incremental heating age determinations for lava flows from the Mandla lobe of the eastern Deccan volcanic province

Sample	Material	Total Fusion Age (Ma)	2σ error	Plateau Age (Ma)	2σ error	N	MSWD	Isochron Age (Ma)	2σ error	$^{40}Ar/^{36}Ar$ initial	2σ error	J
PLB F12/S12	plagioclase	63.91	0.52	64.08	0.51	9/10	0.97	64.01	0.87	294.2	25.5	0.002013
SK F10/S10	plagioclase	64.34	0.72	64.41	0.65	8/8	0.12	64.45	1.23	294.7	15.8	0.001868
BG F5/S5	whole rock	42.77	0.46	47.74	0.53	5/11	0.18	48.09	16.47	294.1	66.3	0.001849
KWR F4/S4	whole rock	62.74	0.75	60.60	0.61	5/11	0.81	59.04	3.18	302.1	13.2	0.002039
LC F1/S1	whole rock	51.96	0.37	61.38	0.42	8/13	1.10	61.58	0.87	289.3	19.4	0.002029
NL F2/S2	plagioclase	63.33	1.19	63.99	1.21	8/10	1.37	60.69	3.74	301.6	6.6	0.001993
MK6	plagioclase	65.35	1.37	65.18	1.22	8/8	0.33	64.78	1.72	301.2	49.3	0.001887
MK2	plagioclase	62.81	1.32	63.51	1.18	7/8	0.32	65.13	2.92	261.0	56.0	0.001906

Ages calculated using biotite monitor FCT-3 (28.201 Ma; Kuiper et al., 2008) are reported in online Appendix 1. For this table, Figure 3 and in the text, we have adjusted those ages to FCs sanidine (Daze et al., 2003).The total decay constant λ = 5.530E-10/yr. N is the number of heating steps (defining plateau/total);MSWD is an F-statistic that compares the variance within step ages with the variance about the plateau age. J combines the neutron fluence with the monitor age.

Fig. 1



72°E
76°E
80°E
24°N
20°N
16°N
= Area of Present Study
CDIC= Chakhla Delakhari Instrusive Complex
MANDLA LOBE
MALWA PLATEAU
Amarkantak
Jabalpur
Namada R.
CDIC
Mandla
Toranmal
SAURASHTRA PLATEAU
Chikaldara
Nagpur
MAIN DECCAN
Igatpuri
Kalsubai
Bombay
Bushe
Ambenali
Mahabaleshwar
Godavari R.
Rajahmundri
Desur
(a)
Group
Subgroup
Formation
DECCAN BASALT
Wai
Desur (~100 m)
Panhala (>175 m)
Mahbaleswar (280 m)
Ambenali (500 m)
Poladpur (375 m)
Lonavala
Bushe (325 m)
Khandala (140 m)
Kalsubai
Bhimashankar (140 m)
Thakurvadi (650 m)
Neral (100 m)
Igatpuri-Jawahar(<700 m)
(b)

Fig. 2

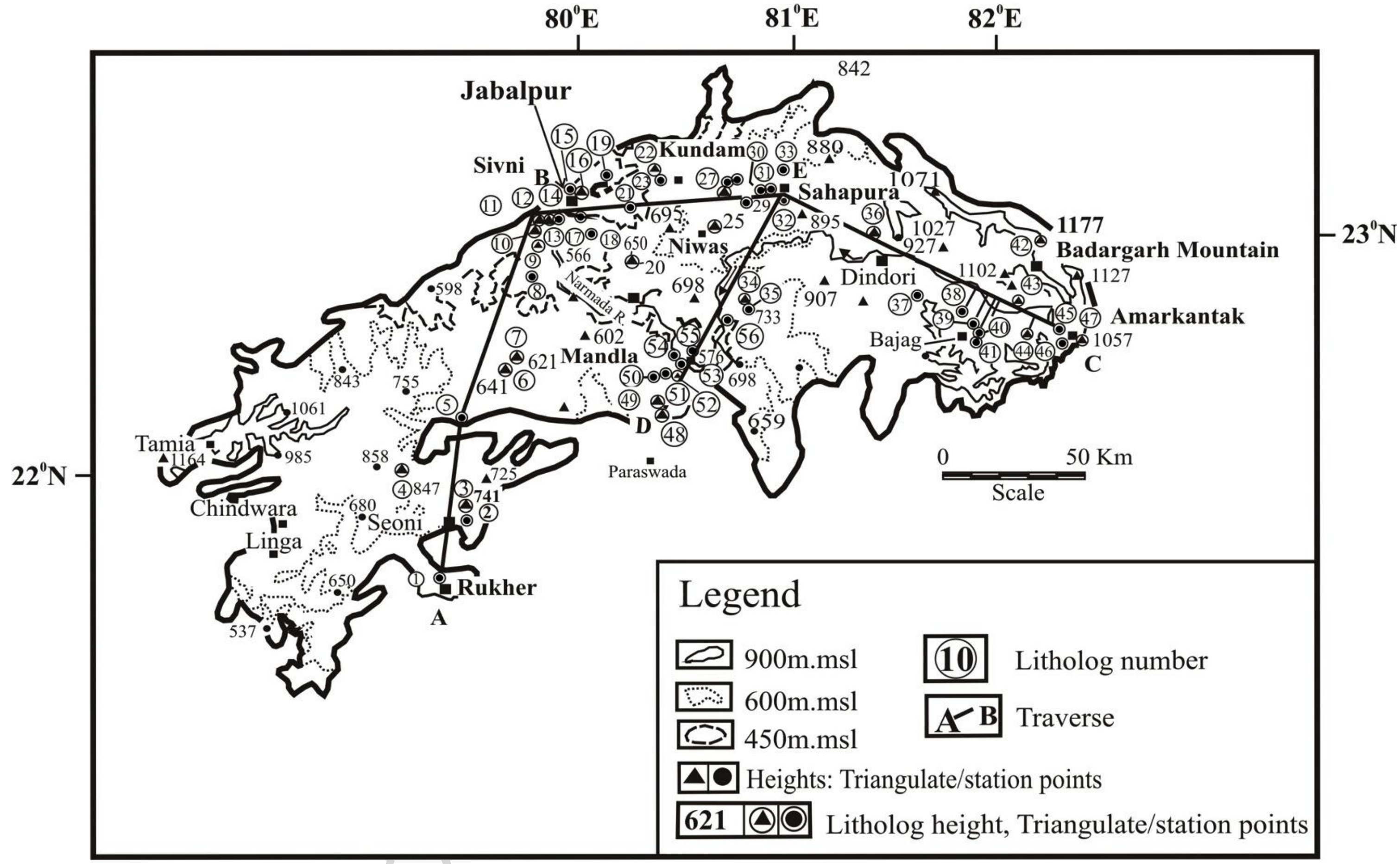

80°E
81°E
82°E
23°N
22°N
Jabalpur
Sivni
Kundam
Sahapura
Niwas
Dindori
Badargarh Mountain
Amarkantak
Mandla
Bajag
Tamia
Chindwara
Seoni
Linga
Rukher
Paraswada
Narmada R.
0 50 Km
Scale
Legend
900m.msl
600m.msl
450m.msl
Litholog number
Traverse
Heights: Triangulate/station points
Litholog height, Triangulate/station points

Fig. 3a

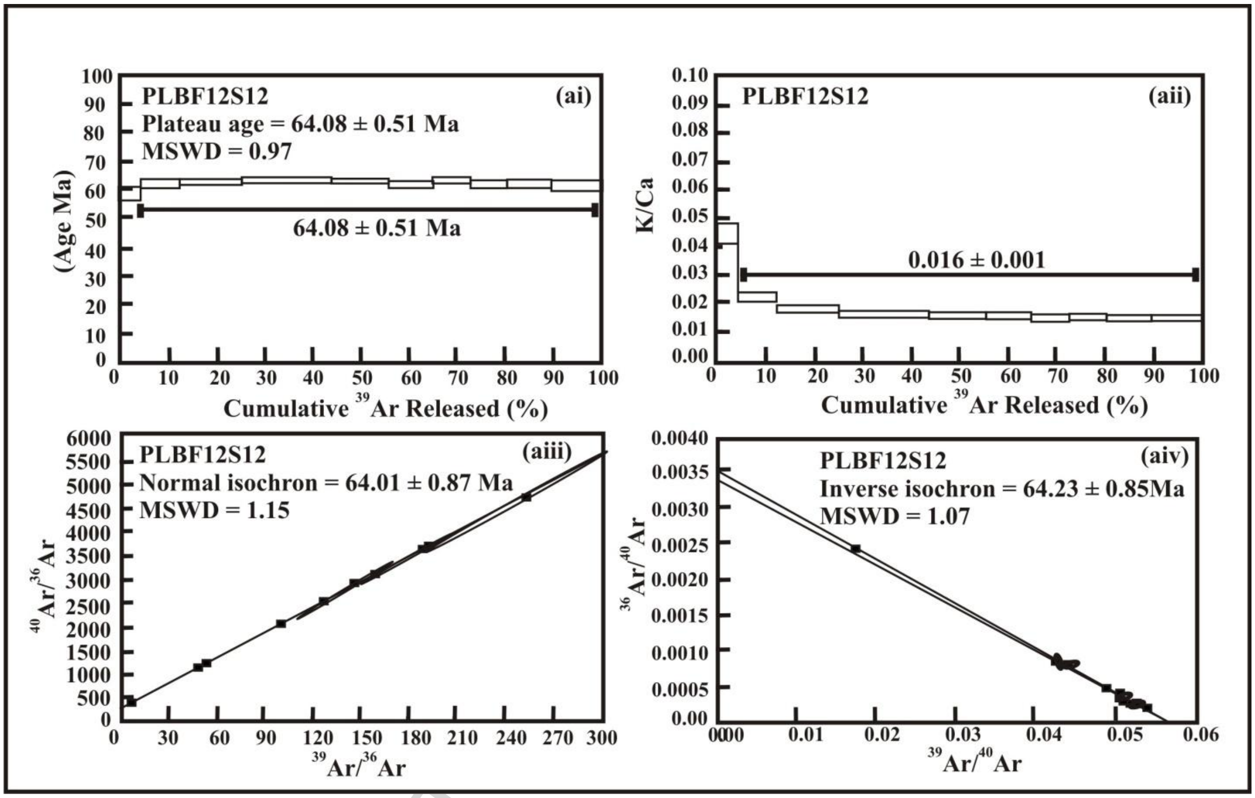

PLBF12S12
(ai)
Plateau age = 64.08 ± 0.51 Ma
MSWD = 0.97
64.08 ± 0.51 Ma
(Age Ma)
Cumulative 39Ar Released (%)
PLBF12S12
(aii)
0.016 ± 0.001
K/Ca
Cumulative 39Ar Released (%)
PLBF12S12
(aiii)
Normal isochron = 64.01 ± 0.87 Ma
MSWD = 1.15
40Ar/36Ar
39Ar/36Ar
PLBF12S12
(aiv)
Inverse isochron = 64.23 ± 0.85Ma
MSWD = 1.07
36Ar/40Ar
39Ar/40Ar

Fig. 3b

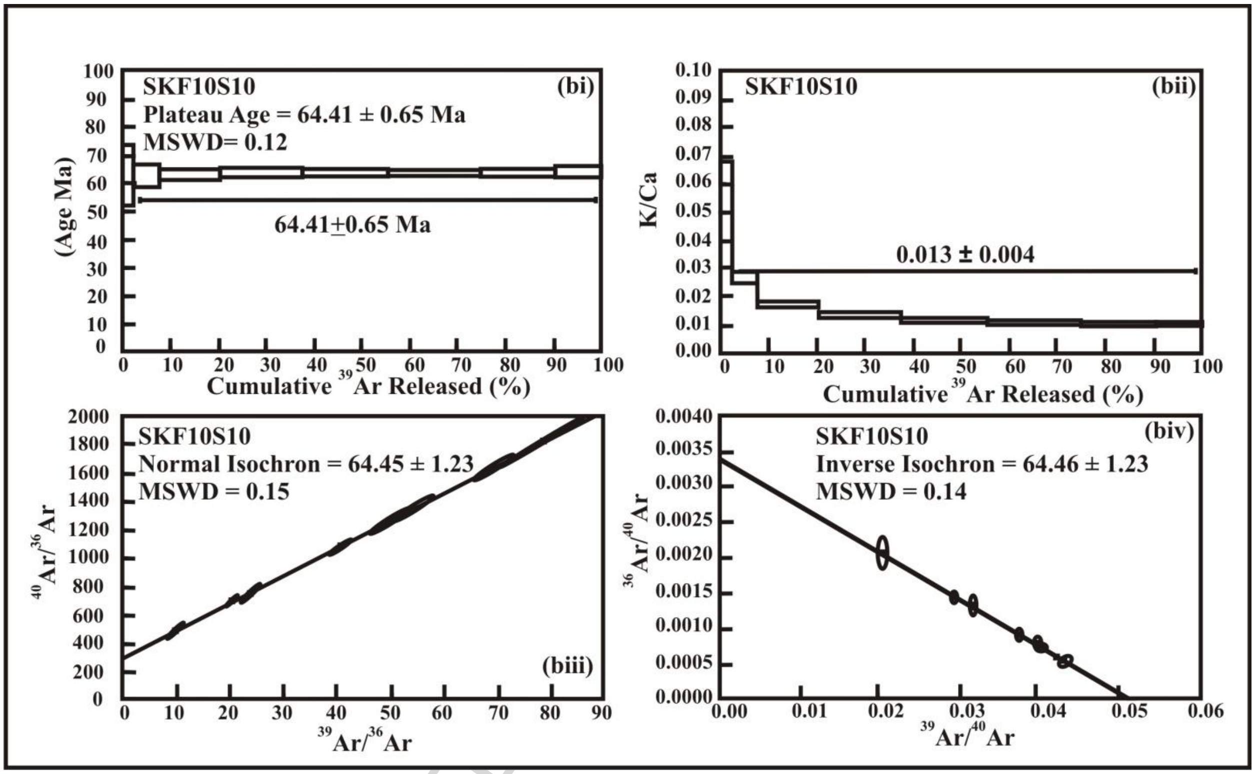
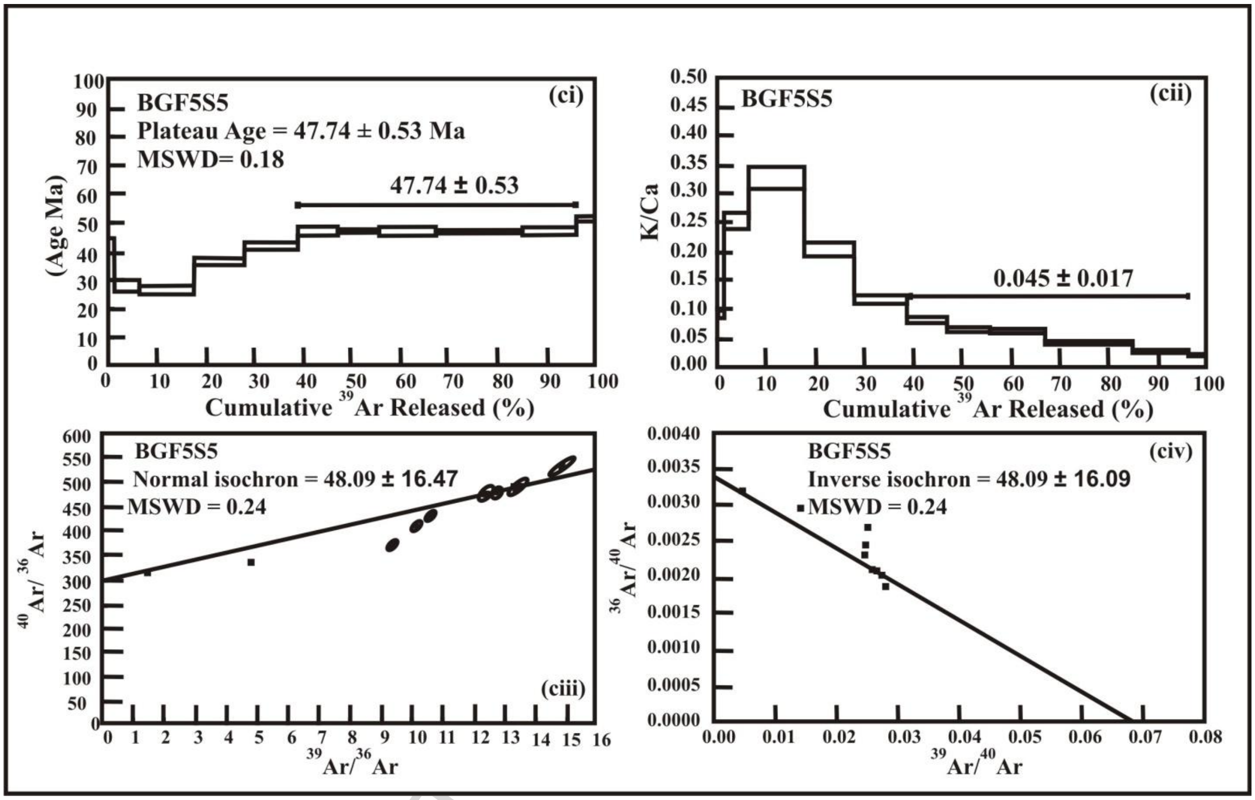

SKF10S10
Plateau Age = 64.41 ± 0.65 Ma
MSWD= 0.12
(bi)
64.41±0.65 Ma
(Age Ma)
Cumulative 39Ar Released (%)
SKF10S10
(bii)
0.013 ± 0.004
K/Ca
Cumulative 39Ar Released (%)
SKF10S10
Normal Isochron = 64.45 ± 1.23
MSWD = 0.15
(biii)
40Ar/36Ar
39Ar/36Ar
SKF10S10
Inverse Isochron = 64.46 ± 1.23
MSWD = 0.14
(biv)
36Ar/40Ar
39Ar/40Ar

Fig. 3c



BGF5S5
Plateau Age = 47.74 ± 0.53 Ma
MSWD= 0.18
(ci)
47.74 ± 0.53
(Age Ma)
Cumulative 39Ar Released (%)
BGF5S5
(cii)
0.045 ± 0.017
K/Ca
Cumulative 39Ar Released (%)
BGF5S5
Normal isochron = 48.09 ± 16.47
MSWD = 0.24
(ciii)
40Ar/36Ar
39Ar/36Ar
BGF5S5
Inverse isochron = 48.09 ± 16.09
MSWD = 0.24
(civ)
36Ar/40Ar
39Ar/40Ar

Fig. 3d

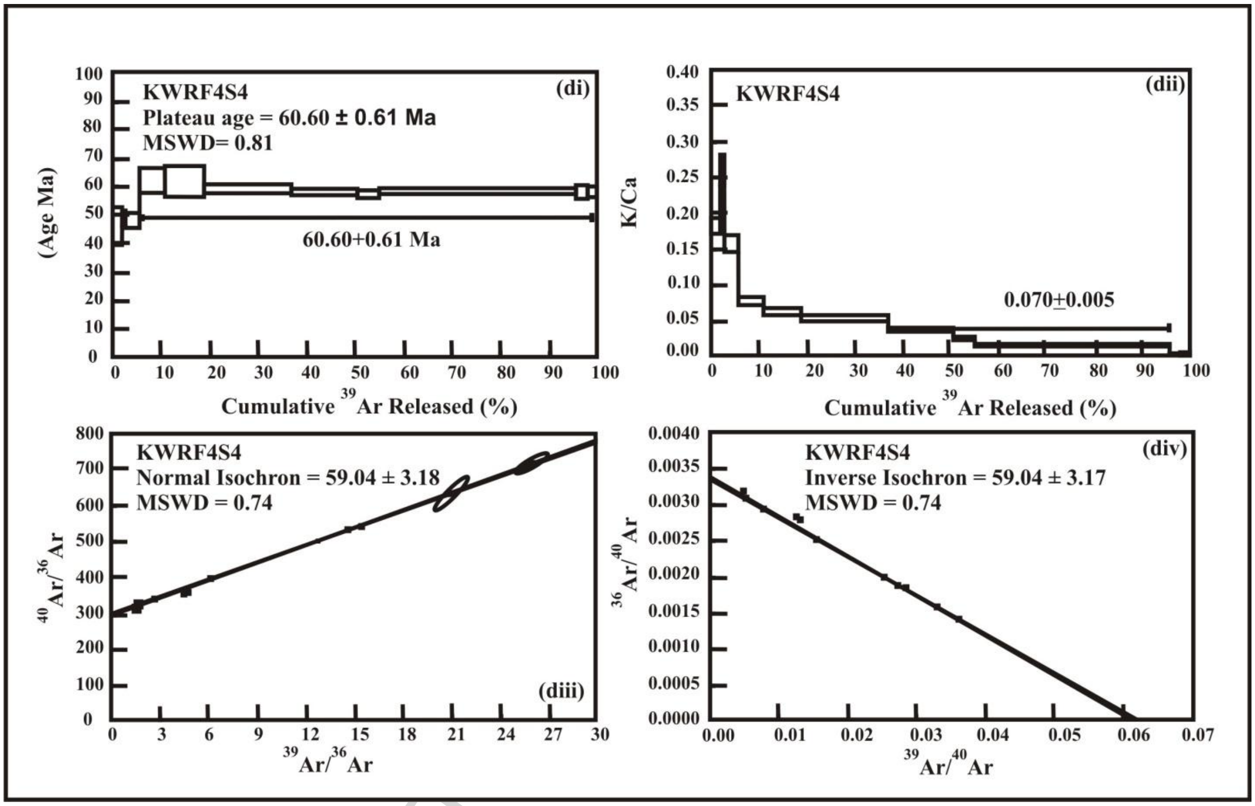
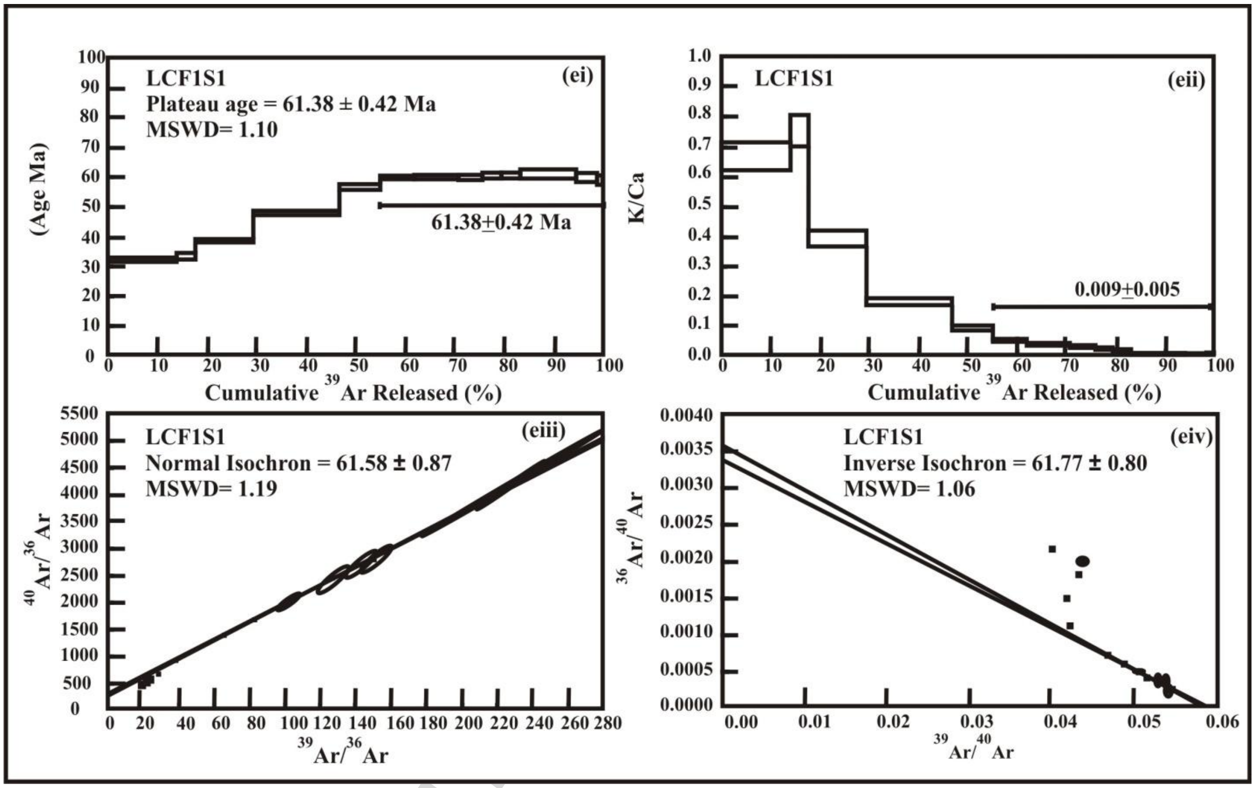
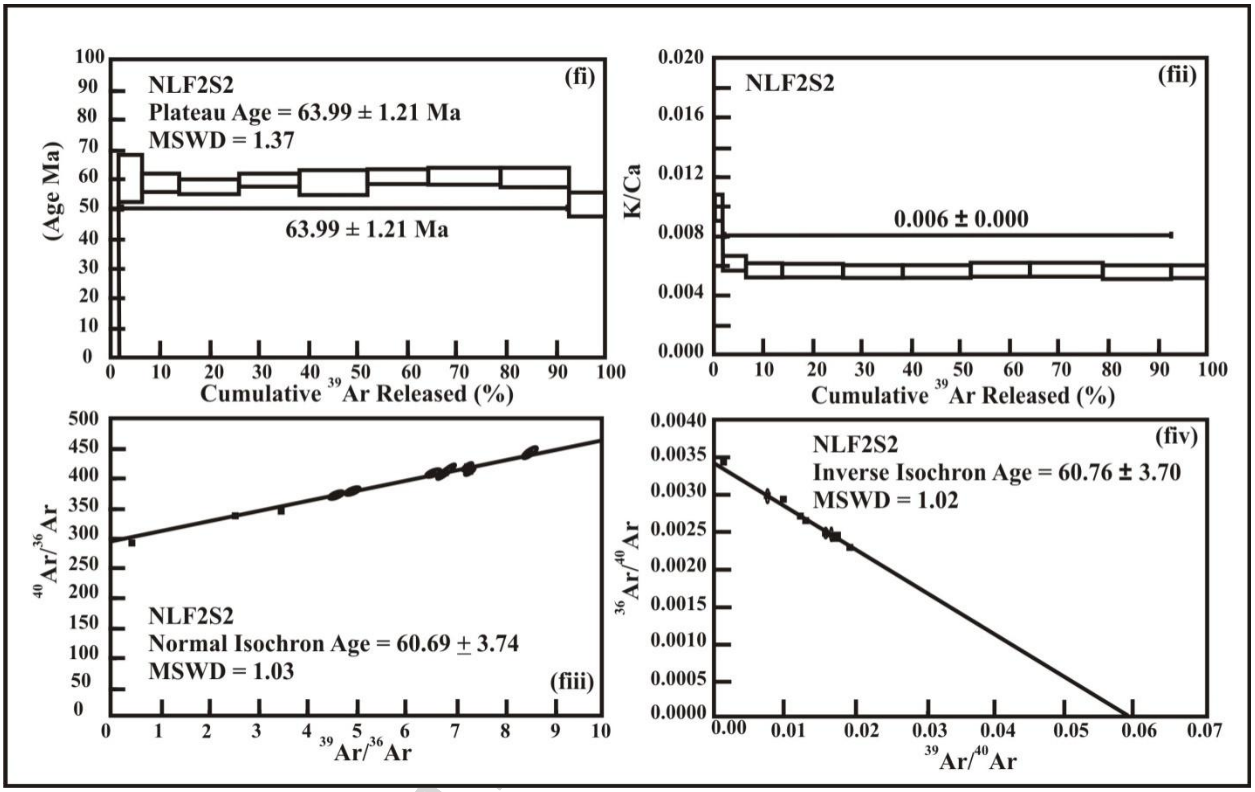

KWRF4S4
Plateau age = 60.60 ± 0.61 Ma
MSWD= 0.81
(di)
60.60+0.61 Ma
(Age Ma)
Cumulative 39Ar Released (%)
KWRF4S4
(dii)
0.070±0.005
K/Ca
Cumulative 39Ar Released (%)
KWRF4S4
Normal Isochron = 59.04 ± 3.18
MSWD = 0.74
(diii)
40Ar/36Ar
39Ar/36Ar
KWRF4S4
Inverse Isochron = 59.04 ± 3.17
MSWD = 0.74
(div)
36Ar/40Ar
39Ar/40Ar

Fig. 3e



LCF1S1
(ei)
Plateau age = 61.38 ± 0.42 Ma
MSWD= 1.10
61.38±0.42 Ma
(Age Ma)
Cumulative 39Ar Released (%)
LCF1S1
(eii)
0.009±0.005
K/Ca
Cumulative 39Ar Released (%)
LCF1S1
(eiii)
Normal Isochron = 61.58 ± 0.87
MSWD= 1.19
40Ar/36Ar
39Ar/36Ar
LCF1S1
(eiv)
Inverse Isochron = 61.77 ± 0.80
MSWD= 1.06
36Ar/40Ar
39Ar/40Ar

Fig. 3f



NLF2S2
Plateau Age = 63.99 ± 1.21 Ma
MSWD = 1.37
(fi)
63.99 ± 1.21 Ma
(Age Ma)
Cumulative 39Ar Released (%)
NLF2S2
(fii)
0.006 ± 0.000
K/Ca
Cumulative 39Ar Released (%)
NLF2S2
Normal Isochron Age = 60.69 ± 3.74
MSWD = 1.03
(fiii)
40Ar/36Ar
39Ar/36Ar
NLF2S2
Inverse Isochron Age = 60.76 ± 3.70
MSWD = 1.02
(fiv)
36Ar/40Ar
39Ar/40Ar

Fig. 3g

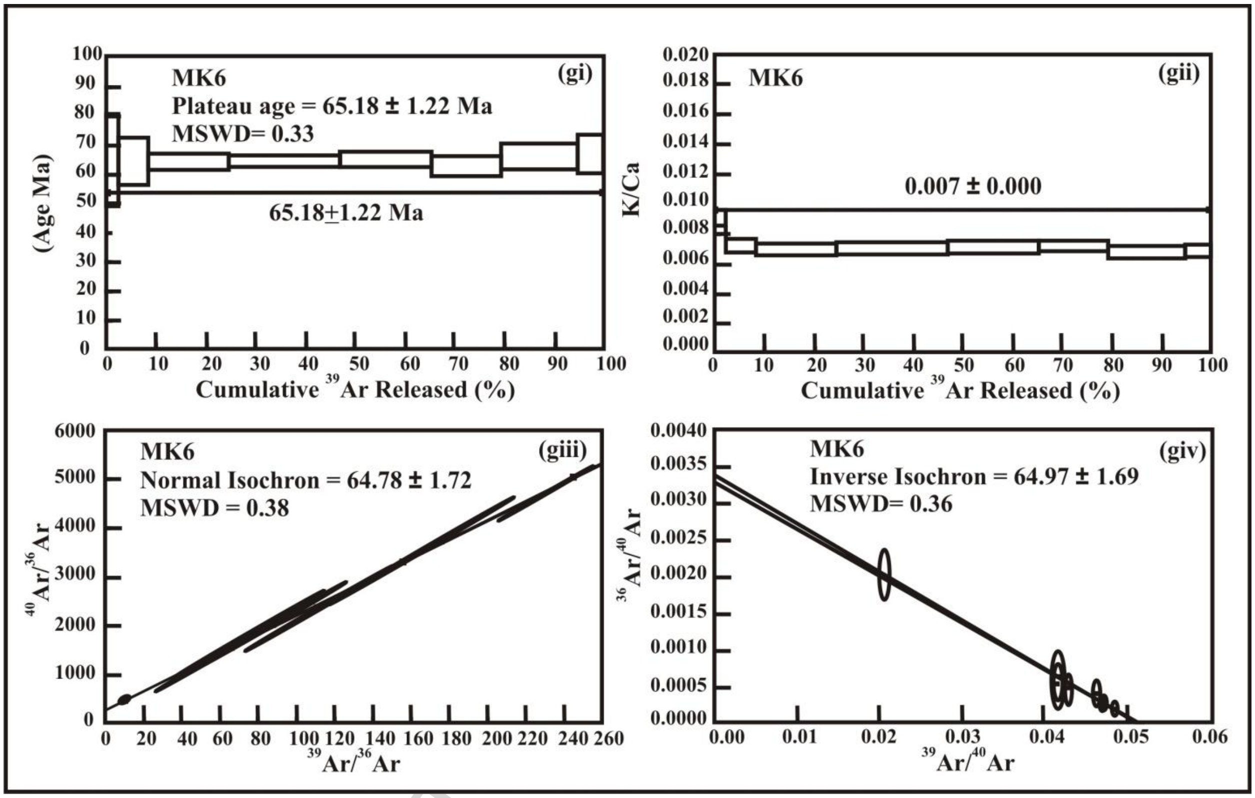
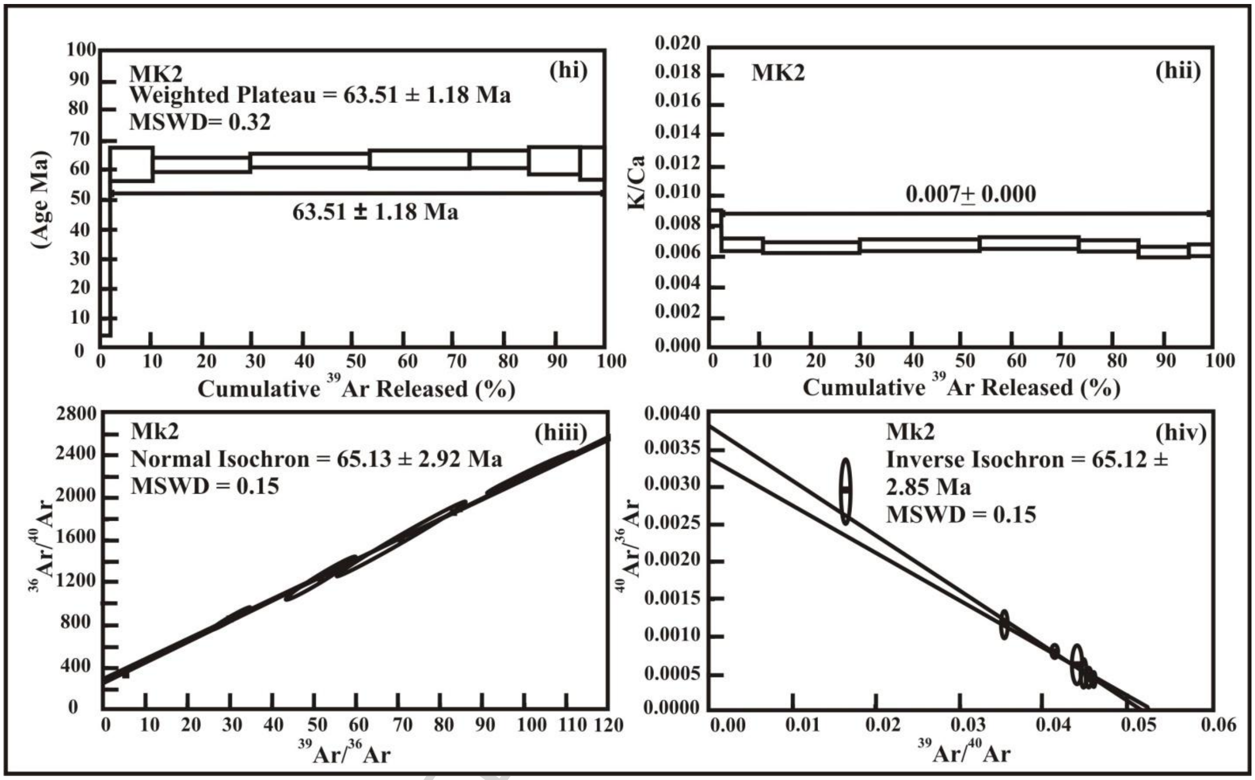

MK6
(gi)
Plateau age = 65.18 ± 1.22 Ma
MSWD= 0.33
65.18±1.22 Ma
(Age Ma)
Cumulative 39Ar Released (%)
MK6
(gii)
0.007 ± 0.000
K/Ca
Cumulative 39Ar Released (%)
MK6
(giii)
Normal Isochron = 64.78 ± 1.72
MSWD = 0.38
40Ar/36Ar
39Ar/36Ar
MK6
(giv)
Inverse Isochron = 64.97 ± 1.69
MSWD= 0.36
36Ar/40Ar
39Ar/40Ar

Fig. 3h



MK2
(hi)
Weighted Plateau = 63.51 ± 1.18 Ma
MSWD= 0.32
63.51 ± 1.18 Ma
(Age Ma)
Cumulative 39Ar Released (%)
MK2
(hii)
0.007± 0.000
K/Ca
Cumulative 39Ar Released (%)
Mk2
(hiii)
Normal Isochron = 65.13 ± 2.92 Ma
MSWD = 0.15
36Ar/40Ar
39Ar/36Ar
Mk2
(hiv)
Inverse Isochron = 65.12 ± 2.85 Ma
MSWD = 0.15
40Ar/36Ar
39Ar/40Ar

Fig. 4

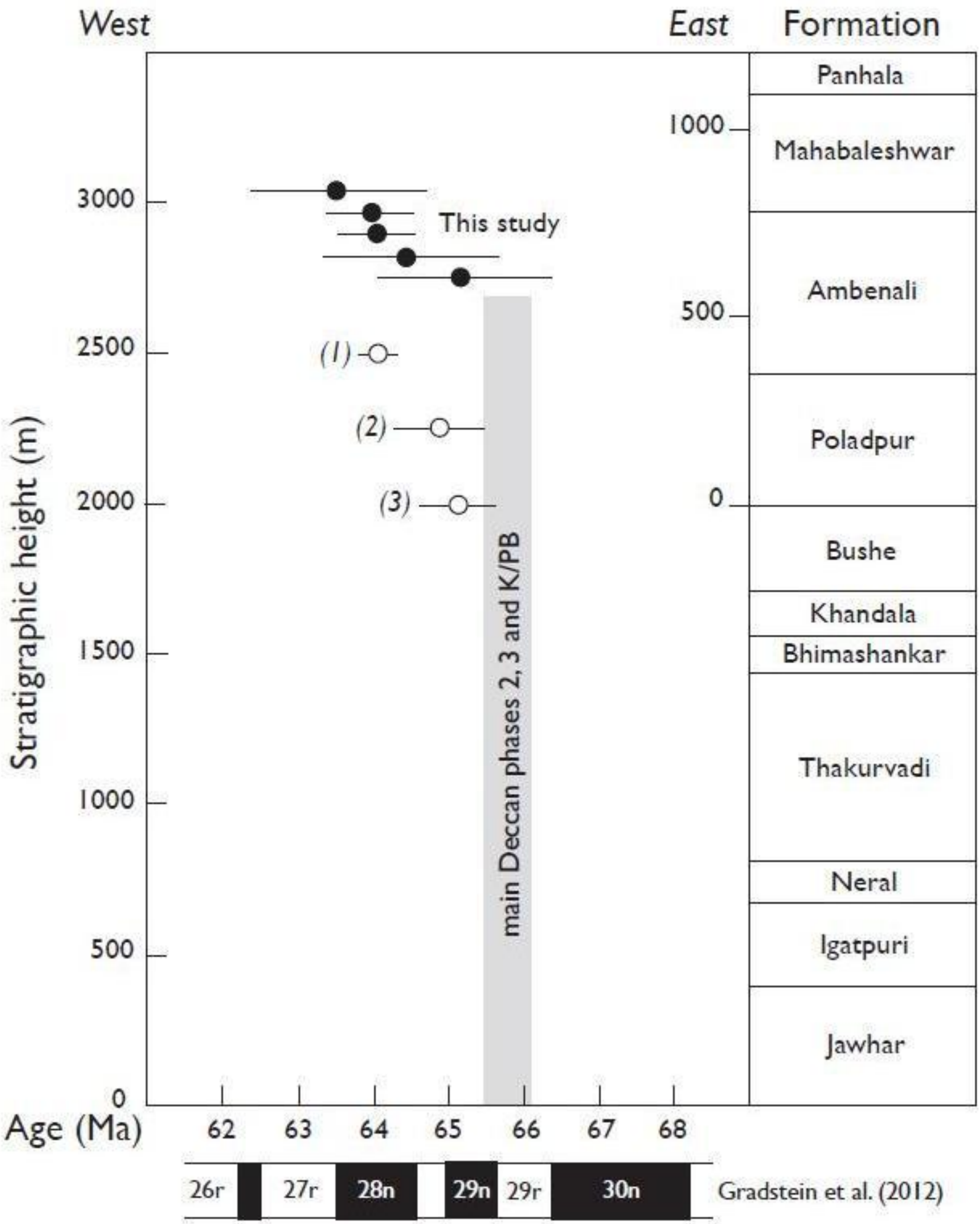

West
East
Formation
Panhala
Mahabaleshwar
Ambenali
Poladpur
Bushe
Khandala
Bhimashankar
Thakurvadi
Neral
Igatpuri
Jawhar
1000
500
0
3000
2500
2000
1500
1000
500
0
This study
(1)
(2)
(3)
main Deccan phases 2, 3 and K/PB
Stratigraphic height (m)
Age (Ma)
62
63
64
65
66
67
68
26r
27r
28n
29n
29r
30n
Gradstein et al. (2012)

Table caption:

Table 1 ^{40}Ar-^{39}Ar incremental heating age determinations for lava flows from the Mandla Lobe of the eastern Deccan volcanic province.

Figure captions:

Fig. 1.(a) Location map (after Shrivastava et al., 2014) forDeccan volcanic province showing area of present study, and (b) southwestern Deccan formational stratigraphy (after Cox and Hawkesworth, 1985; Beane et al., 1986; Subbarao et al., 1988c; Lightfoot et al., 1990).

Fig. 2. (i) Topographic map of the Mandla lobe showing layout of the traverses (A-B, B-C and D-E) and 56 measured sections (after Shrivastava and Ahmad, 2005).

Fig. 3. Data from eight incremental heating experiments on Deccan basalts from the Mandla lobe. In each set (a-h) the upper left panel shows the age spectrum of apparent step ages as a function of cumulative fraction of ^{39}Ar released. The vertical width of the individual steps indicates 2σ error. Plateau age (concordant, contiguous heating steps) with the corresponding 2σ uncertainty is shown with a horizontal bar. The upper right panel shows step K/Ca compositions, calculated from measured $^{39}Ar/^{37}Ar$, plotted against cumulative fraction of ^{39}Ar released. The lower left and right panels display isotope correlation diagrams ($^{40}Ar/^{36}Ar$ vs$^{39}Ar/^{36}Ar$ "normal" and $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ "inverse") for the steps that constitute the plateau, showing2σ error envelopes and the best-fit regression line for each. Normal and inverse isochron ages ($\pm$2σ)and MSWD are given.

Fig. 4. New ^{40}Ar-^{39}Ar plateau ages from plagioclase separates for lava flows bracketing the ~900m exposure at Mandla lobe, eastern Deccan province (filled circles, ±2σ horizontal bars). The Mandla lobe flows correlate geochemically with the upper formations (Mahabaleshwar, Ambenali) found in the SW of the thick western sequence, whose ages (open circles) are reported by (1) Chenet et al. (2007), mean of 4 analyses, and (2) Widdowson et al. (2000), mean of 4 analyses, and with the Rajahmundry lava flows in the SE, whose ages (3) are from Knight et al. (2003), mean of 8 analyses. The main sequence of Deccan lava flows was erupted in <1 m.y. in two intense phases (Chenet et al., 2009) that bracket the K/PB at ~66 Ma. Deccan activity began with smaller phase 1 eruptions (not shown) close to 68 Ma. All ages are calculated relative to standard FCs (28.201 Ma, Kuiper et al., 2008) for comparison with the geomagnetic polarity time scale of Gradstein et al. (2012).

Highlights

- New ^{40}Ar-^{39}Ar ages for 37 eastern Deccan lava flow section.
- No significant age difference (63-65 Ma) detected across the succession.
- Calculated a weighted mean age of 63.9 +/- 0.3 Ma.
- These post-K/PB lavas are younger than the main Deccan lavas (67-65 Ma).
- Chrono-chemical correlation with SW Deccan shows continuity of post-K/PB terminal eruptions.

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