An Ediacaran–Cambrian thermal imprint in Rajasthan, western India: Evidence from ^{40}Ar – ^{39}Ar geochronology of the Sindreth volcanics

ARCHISMAN SEN¹, KANCHAN PANDE¹, HETU C SHETH^{1,*}, KAMAL KANT SHARMA²,
SHRABONI SARKAR¹, A M DAYAL³ and HARISH MISTRY²

¹*Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.*

²*Government Postgraduate College, Sirohi 374 001, Rajasthan, India.*

³*National Geophysical Research Institute, Hyderabad 500 007, India.*

**Corresponding author. e-mail: hcsheth@iitb.ac.in*

The Sindreth Group exposed near Sirohi in southern Rajasthan, western India, is a volcanosedimentary sequence. Zircons from Sindreth rhyolite lavas and tuffs have yielded U–Pb crystallization ages of ~768–761 Ma, suggesting that the Sindreth Group is a part of the Malani magmatic event. Earlier ^{40}Ar – ^{39}Ar studies of other Malani volcanic and plutonic rocks yielded disturbed argon release spectra, ascribed to a ~550 Ma thermal event possibly related to the Pan-African orogeny. To test and confirm this possibility, we dated two whole-rock and three feldspar separate samples of the Sindreth volcanics by the ^{40}Ar – ^{39}Ar method. All samples yield disturbed argon release spectra suggesting radiogenic argon loss and with plateau segments at 550 Ma or 490 Ma. We interpret these as events of argon loss at 550–490 Ma related to an Ediacaran–Cambrian thermal event, possibly related to the Malagasy orogeny. The combined older and new ^{40}Ar – ^{39}Ar results are significant in showing that whereas Ediacaran–Cambrian magmatic and metamorphic events are well known from many parts of India, they left thermal imprints in much of Trans-Aravalli Rajasthan as well. The overall evidence is consistent with a model of multiphase assembly of Gondwanaland from separate continental landmasses.

1. Introduction: The Aravalli Craton of Rajasthan

The Aravalli Craton of western India (figure 1a) spans a geological history of >3.3 billion years (e.g., Choudhary *et al.* 1984; Roy 1988; Gopalan *et al.* 1990; Wiedenbeck *et al.* 1996; Roy and Jakhar 2002; Meert *et al.* 2010; Roy *et al.* 2012). Its Archaean record is represented by the Banded Gneissic Complex consisting of gneisses, metasediments and

ultramafic rocks, with extensive metamorphism and granite plutonism. Roy (1988, 1990) suggested the term Mewar Gneiss for the true basement over which major stratigraphic sequences of Rajasthan (the Palaeoproterozoic Aravalli and the Mesoproterozoic Delhi Supergroups) were deposited (e.g., Ahmad *et al.* 2008). The Delhi Supergroup forms the backbone of the NE–SW-trending Aravalli mountain range (figure 1a), and both Supergroups have undergone intense deformation, polyphase

Keywords. Gondwanaland; India; Rajasthan; Sirohi; Sindreth; geochronology.

Figure 1. (a) Outline map of India showing its major Precambrian cratons and fold belts (thick grey lines). Some localities are also marked. (b) Geological map of the Sirohi region of southern Rajasthan, with Sirohi and some other localities marked, and the extent of the geological units including the Sirohi Group. Modified from De Wall *et al.* (2012).

metamorphism, and granite plutonism (e.g., Biswal 1988). The Trans-Aravalli region, west of the Aravalli Range, is occupied by post-Delhi (873–800 Ma) granites, collectively called the Erinpura

Granite, with shear overprinting, metamorphism and migmatization between 779 and 736 Ma (Van Lente *et al.* 2009; Just *et al.* 2011) (figure 1b). A major, little deformed Proterozoic sedimentary sequence in southeastern Rajasthan is the Vindhyan Supergroup (e.g., Ray 2006; Malone *et al.* 2008). The Erinpura granites are followed by the voluminous Malani granite-rhyolite magmatism (Coulson 1933; Bhushan and Chandrasekaran 2002; Sharma 2004, 2005; De Wall *et al.* 2010, 2012). Whereas Rb–Sr isochron ages of these range from 779–680 Ma (Crawford 1970; Crawford and Compston 1970; Kochhar *et al.* 1985; Rathore 1994; Dhar *et al.* 1996; Rathore *et al.* 1996, 1999), U–Pb zircon ages and palaeomagnetic data suggest a much narrower duration from ~771–761 Ma (Torsvik *et al.* 2001; Gregory *et al.* 2009; Van Lente *et al.* 2009; Khan *et al.* 2012; Rao *et al.* 2012).

2. The problem, and objectives of this study

The Aravalli Craton is not known to have experienced any significant tectonic deformation episodes since the ~760 Ma Malani magmatism. Rathore *et al.* (1996) obtained the oldest Rb–Sr isochron age of 779 ± 10 Ma on andesite-dacite-rhyolite lavas from the Dir–Gurapratapsingh area (figure 1a). They also performed ^{40}Ar – ^{39}Ar step heating studies on a basalt, a dacite and a rhyolite. They obtained disturbed argon release spectra, with broadly increasing apparent ages for progressively higher-temperature steps and short plateau-like segments of 550 Ma age. They noted that the patterns were suggestive of loss of radiogenic argon due to secondary thermal episodes like metamorphism, as shown in several studies of micas (e.g., Pankhurst *et al.* 1973; Roddick *et al.* 1980; Phillips and Onstotte 1986; Zeitler 1987). Rathore *et al.* (1996) therefore interpreted their argon release spectra as indicating that the Malani volcanic rocks of Dir–Gurapratapsingh had suffered partial diffusive loss of radiogenic argon during a thermal event around 550–500 Ma.

In a subsequent study, Rathore *et al.* (1999) reported a Rb–Sr isochron age of 681 ± 20 Ma for Malani rhyolites of Manihari in the same area. They also provided Rb–Sr isochron ages of two major Malani granite plutons: the Jalore granite (727 ± 8 Ma) and the Siwana granite (698 ± 10 Ma) (figure 1a). Rathore *et al.* (1999) also dated two samples of the Jalore granite with the ^{40}Ar – ^{39}Ar method, and obtained disturbed argon release spectra showing argon loss and plateau-like segments with ages of ~550 Ma. They interpreted this, as well as their earlier ^{40}Ar – ^{39}Ar results on the

Diri–Gurapratapsingh lavas (Rathore *et al.* 1996), as reflecting thermal imprints of the Pan-African orogeny in the Trans-Aravalli region.

We think that the ^{40}Ar – ^{39}Ar results of Rathore *et al.* (1999) on the Jalore granite cannot be unambiguously interpreted as showing a later thermal disturbance because of the very slow cooling of granite plutons, leading to diffusive argon loss for tens of millions of years. The 550 Ma parts of the spectra obtained by Rathore *et al.* (1999) on the Jalore granite may simply reflect closure of the system to diffusive argon loss at 550 Ma, rather than a thermal disturbance. However, a 550–500 Ma thermal imprint becomes much more convincing, when the rocks dated by the ^{40}Ar – ^{39}Ar technique are lava flows, as is the case in the earlier study of Rathore *et al.* (1996). However, there have been no subsequent ^{40}Ar – ^{39}Ar studies of Malani volcanics which might have supported or contradicted the important possibility of a Pan-African thermal imprint in this region. Therefore, it is to evaluate this possibility, that we took up a ^{40}Ar – ^{39}Ar geochronological study of a different volcanic suite from the Malani magmatic province, namely the Sindreth Group.

3. The Sindreth Group

A metapelitic and metacarbonate sequence of Middle to Late Neoproterozoic age called the Sirohi Group is exposed to the west of the Delhi fold belt, and is intruded by the Erinpura Granite (Sharma 1996, 2004; Roy and Sharma 1999; Purohit *et al.* 2012) (figure 1b). The Sirohi Group shows a single phase of simple shear deformation, compared to the multiphase deformation in the Delhi Supergroup (Sharma 1996; Roy and Sharma 1999). A volcanic sequence exposed within the Erinpura Granite near Sirohi town (figure 1b) is known as the Sindreth Group (Sharma 1996, 2004; Roy and Sharma 1999; Van Lente *et al.* 2009; Rao *et al.* 2012; Sen 2012). The Sindreth Group (figure 2) consists of a sequence of basal polymictic conglomerate derived from the Erinpura Granite and the Sirohi Group metasediments, overlain by lava flows of basalt, rhyolite, finely laminated rhyolitic tuffs and chert, followed by arkose and conglomerate. The basalt flows sometimes show pillow structures and spilitization, indicating subaqueous (possibly submarine) eruptions, and are hydrothermally altered. The tuffs show evidence for penecontemporaneous deformation and along with the cherts suggest deposition in water. The rhyolite lavas are best exposed in the Pamta Hill near Sindreth village (figure 2). A NW–SE dyke swarm of feldspar porphyries (and subordinate dolerites) is exposed

Figure 2. Map of the Sindreth Group with sample locations marked. Based on Sharma (2004) and Sen (2012).

in the Erinpura Granite around Dhanta village southeast of Sindreth (figure 2). They cut across a linear metagabbro body which forms a part of the Daba Shear Zone and is described as a possible fragment of oceanic lithosphere (Pandit *et al.* 2011).

The Sindreth Group volcanosedimentary rocks dip by 45°–60° towards the northwest. Roy and Sharma (1999) noted the absence of penetrative deformation in the Sindreth rocks, though the arkose in the upper part of the sequence, exposed near Angor dam (figure 2) shows development of folds along NNE–SSW axes associated with faulting (Sharma 1996; Chore and Mohanty 1998; Sen 2012). De Wall and Pandit (2007) reported magnetic anisotropic fabric from the Sindreth basal

conglomerate. Van Lente *et al.* (2009) dated zircons from three rhyolites by the U–Pb method, and obtained ages ranging from 767 ± 2.9 Ma (2σ) to 761 ± 16 Ma (2σ). More recent U–Pb dating of zircons in the rhyolite and tuffs (Rao *et al.* 2012) also yielded typical Malani ages of 765.1 ± 7.2 Ma (2σ) and 768.2 ± 6.9 Ma (2σ), along with ages of 666–644 Ma on a small zircon population.

4. Petrography and geochemistry

Locations of our study samples are marked on figure 2. The Pamta rhyolite (Sharma 2004) (sample Sind 04) is a highly porphyritic, flesh-red-coloured rhyolite, composed of quartz, K-feldspar, and some plagioclase in a fine-grained groundmass of the same minerals. Some quartz grains show marginal corrosion. The green Angor rhyolite (Sharma 2004) (sample Sind 08) is found only as a small outcrop at the northwestern side of the Pamta Hill near Angor village. It conformably overlies the Pamta rhyolite, and is also highly porphyritic. The mineral assemblage is similar to that of the former, except for some interstitial glass. The finely laminated tuffs show angular rock and quartz fragments in a very fine to glassy groundmass. The Dhanta feldspar porphyry dykes (samples Sind 10, Sind 11) contain large (up to ~ 1 cm) K-feldspar and plagioclase phenocrysts, in a medium-grained groundmass of quartz and feldspars. Detailed petrographic observations and mineral compositions can be found in Van Lente *et al.* (2009).

Major and trace element concentrations in the volcanics and the dykes were determined by X-ray fluorescence (XRF) spectrometry at the National Geophysical Research Institute (NGRI), Hyderabad. Loss on ignition (LOI) was determined gravimetrically by igniting sample powders at 950°C at IIT Bombay. The analytical procedures, data tables and related descriptions and discussions can be found in Sen (2012).

5. ^{40}Ar – ^{39}Ar geochronology

5.1 Methods

Five rock samples, including two whole-rock samples (Sindreth basalt Sind 03WR and Pamta rhyolite Sind 04WR) and three alkali feldspar separates from the rhyolitic rocks (Sind 04P, Sind 08P, Sind 11P) were chosen for dating by the ^{40}Ar – ^{39}Ar incremental heating technique. Rock chips of about 20–25 g were cut from the hand specimens to avoid veins and weathered material.

The chips were crushed in an agate mortar and sieved, the large grains were collected and alkali feldspar grains were separated from them using heavy liquid (sodium polytungstate water solution of specific gravity 2.56). The feldspar grains, and the 120–180 μm size-fractions of the whole-rock samples, were leached with a 1% HCl solution to eliminate secondary carbonates. All these were then cleaned in deionised water in an ultrasonic bath, and then heated in an oven to drive away moisture.

About 0.2 g of each sample was packed in aluminium capsules. The Minnesota hornblende reference material (MMhb-1) of age 523.1 ± 2.6 Ma (Renne *et al.* 1998) and high purity CaF_2 and K_2SO_4 salts were used as monitor samples. High-purity nickel wires were placed in both samples and monitored capsules to monitor the neutron fluence variation, which was typically $\sim 5\%$. The aluminium capsules were kept in a 0.5 mm-thick cadmium cylinder and irradiated in the light-water moderated CIRUS reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for ~ 100 h. Two separate irradiation runs were performed, the first with whole-rock samples Sind 03WR and Sind 04WR, and the other with mineral separate samples Sind 04P, Sind 08P and Sind 11P. The irradiated samples were repacked in aluminium foil and loaded on the extraction unit of a Thermo Fisher Scientific noble gas preparation system. Argon was extracted in a series of steps up to 1600°C in an electrically heated ultra-high vacuum furnace (Appendix 1a–d). After purification using Ti–Zr getters, the argon released in each step was measured with a Thermo Fisher ARGUS mass spectrometer located at the National Facility for ^{40}Ar – ^{39}Ar Geo-thermochronology in the Department of Earth Sciences, IIT Bombay. The mass spectrometer is equipped with five Faraday cups fitted with $10^{11} \Omega$ resistors.

Interference corrections for Ca- and K-produced Ar isotopes, based on the analysis of CaF_2 and K_2SO_4 salts, were $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.00404$, 0.00898, and 0.00054, respectively, for samples Sind 03WR and Sind 04WR. The interference corrections were $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.00052$, 0.00101 and 0.00072, respectively, for samples Sind 04P, Sind 08P and Sind 11P. ^{40}Ar blank contributions were 1–2% or less for all temperature steps (Appendix 1a–d). The irradiation parameter J for each sample was corrected for neutron flux variation using the activity of nickel wires irradiated with each sample. Values of fluence-corrected J for various samples are as follows: Sind 03WR, 0.002791 ± 0.000015 ; Sind 04WR, 0.002729 ± 0.000015 ; Sind 04P, 0.002819 ± 0.000011 ; Sind 08P,

0.002619 ± 0.000011 ; and Sind 11P, 0.002853 ± 0.000011 .

5.2 Results

We define a plateau as that portion of the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum that has four or more consecutive steps with apparent ages within 2σ confidence level and comprising a substantial percentage ($\geq 50\%$) of the total ^{39}Ar release (e.g., Sen 2012; Sen *et al.* 2012). The data were plotted using the program ISOPLLOT v. 3.75 (Ludwig 2012), and all age uncertainties in this paper are reported at the 2σ level.

The two whole-rock samples (Sindreth basalt Sind 03WR and Pamta rhyolite Sind 04WR) did

Figure 3. Argon release spectra for (a) Sind 03WR (Sindreth basalt, whole-rock), and (b) Sind 04WR (Pamta rhyolite, whole-rock).

not yield plateau spectra. Instead, they showed increasing apparent ages with increasing temperature (figure 3a, b). The Sind 03WR pattern is a classic 'ascending staircase' pattern, while the Sind 04WR pattern, except for the three lowermost-temperature steps, is also of this type. Such patterns are caused by loss of radiogenic argon due to a post-crystallisation thermal event, and do not yield any age (e.g., Zeitler 1987; Rathore *et al.* 1996, 1999). Sample Sind 04P shows a plateau with

Figure 4. (a–c) Plateau, isochron and inverse isochron for the 552 Ma plateau segment in sample Sind 04P (feldspar separate).

Figure 5. (a–c) Plateau, isochron and inverse isochron for the 491 Ma plateau segment in sample Sind 08P (feldspar separate). (d–f) ‘Plateau-like’ partial spectrum, isochron and inverse isochron for the sample Sind 11P (feldspar separate).

an age of 552.0 ± 1.1 Ma (figure 4a). The isochron and inverse isochron ages for the relevant steps (figure 4b, c) are statistically indistinguishable from the plateau age. The $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts of the isochrons and inverse isochrons have atmospheric values of this ratio (295.5) within analytical error.

Sample Sind 08P yielded a plateau with 13 overlapping steps and an age of 491.1 ± 0.86 Ma (figure 5a). The isochron and inverse isochron for these steps (figure 5b, c) yield ages of 490.4 ± 9.6 Ma and 491.0 ± 2.9 Ma, respectively, which are both concordant with the plateau age. The $^{40}\text{Ar}/^{36}\text{Ar}$

intercepts of the isochrons and inverse isochrons are atmospheric, though sometimes with high analytical errors. Sample Sind 11P did not yield a plateau, but showed a ‘plateau-like’ part without consecutive steps overlapping at the 2σ confidence level and an age of 498.6 ± 2.1 Ma, albeit with zero probability (figure 5d), and statistically indistinguishable isochron and inverse isochron ages of 496 ± 13 Ma and 496.3 ± 7.3 Ma for the ‘plateau-like’ steps (figure 5e, f). The $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts of the isochrons and inverse isochrons are atmospheric, though sometimes with high analytical errors.

6. Discussion

6.1 Interpretation of the Ar–Ar spectra

Whereas Van Lente *et al.* (2009) and Rao *et al.* (2012) obtained U–Pb zircon ages of 768–761 Ma for the Sindreth Group rhyolites and tuffs, none of the samples of this study yielded comparable ages even for the highest-temperature degassing steps. Argon release spectra like those in figure 3(a, b) are related to argon loss due to some post-crystallisation thermal event and are well known from whole-rock samples, hornblende, K-feldspar, and muscovite (Harrison 1981; McDougall and Harrison 1999; Bhutani *et al.* 2004). Depending on the magnitude of the thermal disturbance reflected in the percentage of argon lost, the date of the younger, low-temperature fractions will be equal to or older than the age of the thermal disturbance, whereas the date of the older, high-temperature fractions will be equal to or younger than the original age of closure (Snee 2002). We therefore consider the younger ^{40}Ar – ^{39}Ar plateau ages as cooling ages reflecting argon resetting in feldspars (with closure temperature of only 150°C, McDougall and Harrison 1999) during the Ediacaran–Cambrian time interval. One of the feldspar samples (Sind 04P) shows imprints of a thermal event at 552 ± 1.7 Ma, while another feldspar sample (Sind 08P) shows such a thermal event at 491.1 ± 1.7 Ma. The third feldspar sample (Sind 11P) shows a similar event at 498.6 ± 2.1 Ma. Thus, two thermal events, at ~ 550 Ma and ~ 490 Ma, seem to have affected the volcanic rocks and led to partial loss of radiogenic argon from them. This is as observed and interpreted by Rathore *et al.* (1996) for the Diri–Gurapratapsingh rhyolites.

6.2 Regional geodynamic scenario

In India 550–490 Ma tectonothermal events are widely known (figure 1a) from the Southern Granulite Terrane of Kerala and Tamil Nadu (e.g., Choudhary *et al.* 1992; Bartlett *et al.* 1996). They are also abundant in the Himalayan region, reflected in the many Late Cambrian to Early Ordovician granites as well as the sedimentary record (e.g., Mehta 1977; Trivedi *et al.* 1984; Garzanti *et al.* 1986; Islam *et al.* 1999). Ediacaran–Cambrian-aged tectonothermal events are also seen in the Eastern Ghats (e.g., Shaw *et al.* 1997; Mezger and Cosca 1999), and in Meghalaya (Ghosh *et al.* 1991). We interpret the 550–490 Ma thermal events identifiable in the argon release patterns of

the Sindreth volcanic rocks as indicating a thermal imprint at that time. The combined older (Rathore *et al.* 1996, 1999) and new (this study) ^{40}Ar – ^{39}Ar results on varied Malani rock suites are significant in showing that whereas Ediacaran–Cambrian magmatic and metamorphic events are well known from many parts of India, they left thermal imprints in much of Trans-Aravalli Rajasthan as well.

India is a key piece of the Gondwanaland jigsaw puzzle. The large landmass of Gondwanaland (figure 6) was formed in the latest Neoproterozoic to early Cambrian time (e.g., Meert 2003; Collins and Pisarevsky 2005), and a clear understanding of these late Proterozoic to Cambrian tectonic events is necessary because they led to major changes in global geology, climate and ecology (e.g., Hoffman *et al.* 1998; Meert and Lieberman 2008). Some workers have suggested that a coherent landmass of East Gondwana (comprising India, Madagascar, Sri Lanka, Australia, and Antarctica) collided with a coherent West Gondwana (comprising mainly Africa and South America) to form Gondwanaland (e.g., Windley *et al.* 1994; Yoshida and Upreti 2006). Others have argued that East Gondwana was never a coherent entity for any length of time, and that Gondwanaland was assembled from many separate continental masses in multiphase orogenic events (e.g., Meert and Van der Voo 1997; Meert 2003; Collins and Pisarevsky 2005).

Widespread 550–490 Ma metamorphic and magmatic activity is well known from various parts of India, Madagascar (e.g., Kröner *et al.* 2000), and East Africa (e.g., Ueda *et al.* 2012), besides other regions. Madagascar collided with East Africa at 650 Ma and experienced extensional collapse at ~ 630 Ma (Paquette and Nédélec 1998), and much of Madagascar experienced thermal overprinting and reworking during 590–500 Ma (Meert 2003 and references therein). Speaking of the eastern Gondwana region as a whole, two main periods of orogenesis have been recognized. First is the 750–620 Ma East African orogeny (Stern 1994; Meert 2003) in which eastern Africa collided with the Arabian–Nubian shield and a poorly defined collage of continental blocks including parts of Madagascar, Sri Lanka, Seychelles, India, and East Antarctica. The second major orogeny is the 570–530 Ma Kuunga orogeny (Meert *et al.* 1995), marking the collision of Australia with India's eastern margin. At the same time (~ 550 Ma) India on its western side was sutured together with Seychelles and Madagascar to form Gondwanaland, and Collins and Pisarevsky (2005) have termed this the Malagasy orogeny. Post-Gondwana-assembly orogenic

Figure 6. Reconstruction of Gondwanaland in Cambrian–Ordovician time, showing cratonic regions, Grenville-age orogens, and Neoproterozoic–Cambrian orogens. Based on McQuarrie *et al.* (2013).

events continued until the Late Ordovician (420 Ma) (Meert 2003; Meert and Lieberman 2008).

We interpret our ^{40}Ar – ^{39}Ar dating results on the Sindreth Group, as well as those of Rathore *et al.* (1996) on the Diri–Gurapratapsingh volcanics, in the framework of the Malagasy orogeny (Collins and Pisarevsky 2005). The combined results appear consistent with a model of multiphase Gondwana amalgamation in the latest Proterozoic to Early Cambrian time (Meert 2003; Collins and Pisarevsky 2005).

7. Conclusions

This ^{40}Ar – ^{39}Ar geochronological study shows an Ediacaran–Cambrian (550–490 Ma) thermal imprint in the Neoproterozoic (~760 Ma) Malani volcanic rocks of the Sindreth Group in southern Rajasthan, western India. It supports the results and conclusions of previous ^{40}Ar – ^{39}Ar geochronological work on Malani volcanic rocks exposed to the north and northwest of the study area (Rathore *et al.* 1996, 1999). Noting the geographic extent of the region between Sindreth, Jalore, and Diri–Gurapratapsingh, the Ediacaran–Cambrian (550–490 Ma) thermal imprint is widespread in the Trans-Aravalli region. This region can thus be added to the list of regions

of the Indian subcontinent from which Ediacaran–Cambrian-aged tectonothermal events are well known, and the thermal events identified in Trans-Aravalli Rajasthan can be ascribed to the 550 Ma Malagasy orogeny (Collins and Pisarevsky 2005).

Acknowledgements

Field work was supported by the Industrial Research and Consultancy Centre (IRCC), IIT Bombay grant 03IR014 to Sheth and a contingency grant from the University Grants Commission, Central Region Office, Bhopal, to Sharma. Sen was supported by a research fellowship from the Council of Scientific and Industrial Research (CSIR), Govt. of India. Pande acknowledges grant No. IR/S4/ESF-04/2003 from the Department of Science and Technology (Govt. of India) towards the development of the IIT Bombay-DST National Facility for ^{40}Ar – ^{39}Ar Geo-thermochronology. Sapna Shinde and L S Mombasawala are thanked for help with the argon work. The authors also thank S Balakrishnan, T K Biswal, Aswini Kumar Choudhary, Ernst Hegner, George Mathew, and Malay Mukul for discussions, and two anonymous reviewers and the Associate Editor Talat Ahmad for helpful critical reviews which improved the manuscript.

Appendix 1(a). Argon isotopic composition and apparent ages of sample **Sind 03WR** (Basalt whole rock) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . The data are interference, decay and mass fractionation corrected. J value is 0.002791 ± 0.000015 .

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
450	300.56 2.84	1.885 0.010	37.215 0.176	521.414 3.043	65.18 33.97 (33.97)	1.68	1
500	296.76 2.96	1.625 0.010	24.282 0.177	453.045 2.713	12.37 27.39 (27.39)	0.43	2.1
550	301.36 2.87	2.055 0.010	33.661 0.176	578.384 3.414	79.36 34.29 (34.29)	1.94	3
600	440.32 56.51	0.189 0.010	22.480 1.751	43.219 0.999	87.50 20.66 (20.67)	32.89	9.7
650	860.20 297.62	0.148 0.010	27.782 1.751	30.544 0.974	129.71 20.45 (20.46)	65.65	14.5
700	997.76 303.32	0.145 0.010	25.826 1.775	40.434 1.011	177.49 19.73 (19.75)	70.38	19.3
750	662.43 78.76	0.190 0.010	20.914 1.764	69.520 1.034	224.15 19.60 (19.63)	55.39	24.6
800	610.83 53.87	0.211 0.010	16.882 1.760	87.114 1.399	248.85 19.81 (19.85)	51.62	31.5
850	739.62 67.89	0.185 0.010	12.348 1.758	100.113 1.276	311.78 18.10 (18.17)	60.05	40.5
900	618.35 36.07	0.249 0.010	8.426 1.756	132.632 1.223	342.45 18.55 (18.63)	52.21	51
950	742.65 46.09	0.222 0.010	5.474 1.749	148.609 1.160	420.61 17.46 (17.58)	60.21	63.9
1000	695.44 39.95	0.246 0.010	7.101 1.753	151.126 1.238	415.53 18.26 (18.36)	57.51	74.4
1050	687.02 36.97	0.265 0.010	7.974 1.752	159.971 1.292	436.85 18.83 (18.95)	56.99	83.8
1100	802.62 45.14	0.307 0.010	20.491 1.753	179.575 1.394	591.45 22.59 (22.75)	63.18	90.8
1150	730.05 32.67	0.344 0.010	14.035 1.763	209.839 1.606	605.42 22.30 (22.47)	59.52	97.1
1200	364.08 4.39	1.647 0.010	32.845 1.769	551.124 4.126	620.95 87.77 (87.81)	18.84	98.1
1250	351.39 3.58	1.896 0.005	42.584 0.177	605.800 4.867	652.03 31.13 (31.27)	15.91	98.8
1300	339.44 3.32	2.036 0.005	51.513 0.178	620.387 4.774	628.80 37.02 (37.13)	12.95	99.5
1350	335.32 3.69	2.216 0.005	53.717 0.180	670.275 5.557	644.16 44.10 (44.19)	11.88	100
Total	527.21 6.34	0.356 0.003	16.080 0.482	153.635 0.359	359.04 6.25 (6.49)	43.95	100

Appendix 1(b). Argon isotopic composition and apparent ages of sample **Sind 04WR** (Rhyolite whole rock) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . The data are interference, decay and mass fractionation corrected. J value is 0.002729 ± 0.000015 .

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
400	434.50	0.076	15.878	5.307	9.71	31.99	0.1
	161.17	0.001	0.032	1.119	6.65 (6.65)		
450	319.60	0.810	46.909	198.316	122.90	7.54	0.2
	9.66	0.002	0.094	1.343	12.23 (12.24)		
500	342.19	0.724	0.874	246.543	159.62	13.64	0.5
	6.04	0.004	0.017	1.651	9.26 (9.30)		
550	451.39	0.323	1.889	142.159	230.45	34.54	0.9
	7.06	0.003	0.016	1.198	6.30 (6.42)		
600	989.09	0.127	0.493	123.291	383.60	70.12	2.3
	16.60	0.002	0.018	1.064	4.73 (5.09)		
650	1822.12	0.067	0.459	118.159	432.92	83.78	5.6
	35.67	0.001	0.016	1.005	4.11 (4.62)		
700	2633.53	0.042	0.294	108.337	421.38	88.78	11.4
	69.05	0.001	0.016	0.999	4.07 (4.56)		
750	2248.51	0.046	0.281	101.650	390.25	86.86	16.4
	55.75	0.001	0.016	0.998	4.14 (4.57)		
800	2666.91	0.038	0.138	100.826	395.20	88.92	22.2
	75.39	0.001	0.017	0.998	4.11 (4.55)		
850	3013.52	0.033	0.087	98.863	393.11	90.19	28.4
	95.51	0.001	0.017	0.998	4.11 (4.55)		
900	2015.75	0.052	0.000	104.936	394.36	85.34	30.6
	53.90	0.001	0.000	1.016	4.29 (4.714)		
950	1724.81	0.064	0.052	109.802	400.21	82.87	36.1
	32.41	0.001	0.017	0.998	4.11 (4.56)		
1000	2244.87	0.047	0.065	105.852	403.90	86.84	42.2
	52.70	0.001	0.017	0.998	4.09 (4.55)		
1050	2606.18	0.042	0.037	108.322	419.97	88.66	49.7
	66.91	0.001	0.016	0.998	4.05 (4.55)		
1100	2991.61	0.039	0.060	114.719	448.48	90.12	60.6
	81.35	0.001	0.016	0.999	3.99 (4.55)		
1150	3279.23	0.039	0.654	118.179	466.52	90.99	77.4
	94.48	0.001	0.016	1.000	3.98 (4.58)		
1200	3050.46	0.042	0.165	125.603	487.07	90.31	94.4
	77.71	0.001	0.017	1.000	3.92 (4.57)		
1250	1988.07	0.072	0.000	143.298	518.34	85.14	99.3
	32.55	0.001	0.000	1.002	3.87 (4.59)		
1300	630.92	0.369	0.002	232.850	524.96	53.16	99.8
	10.54	0.004	0.000	1.713	7.96 (8.34)		
1350	440.57	0.853	0.002	375.617	524.56	32.93	100
	12.25	0.011	0.000	3.702	18.31 (18.48)		
Total	2229.36	0.053	0.328	116.081	439.05	86.75	100
	14.92	0.000	0.005	0.314	1.267 (2.49)		

Appendix 1(c). Argon isotopic composition and apparent ages of sample **Sind 04P** (Rhyolite Alkali Feldspar phenocryst) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . The data are interference, decay and mass fractionation corrected. J value is 0.002819 ± 0.000011 .

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
700	371.90 3.87	1.648 0.011	0.072 0.004	612.860 4.407	547.85 20.86 (20.95)	20.54	0.8
780	2094.44 28.46	0.085 0.001	0.043 0.001	178.191 0.891	646.97 3.35 (4.00)	85.89	3.5
870	2745.86 41.70	0.053 0.001	0.032 0.001	144.752 0.725	560.09 2.82 (3.42)	89.24	6.2
960	3484.27 42.19	0.033 0.000	0.026 0.001	114.438 0.574	466.60 2.29 (2.83)	91.52	12.8
1060	4548.73 56.59	0.025 0.000	0.050 0.001	113.391 0.567	471.68 2.24 (2.80)	93.5	17
1085	4819.51 48.73	0.024 0.000	0.015 0.001	115.414 0.578	480.70 2.26 (2.83)	93.87	20.1
1105	4097.20 51.22	0.029 0.000	0.014 0.001	120.485 0.603	494.11 2.35 (2.93)	92.79	22.3
1120	3851.22 34.81	0.032 0.000	0.015 0.001	121.487 0.608	495.54 2.361 (2.94)	92.33	24
1135	3407.03 32.75	0.036 0.000	0.017 0.001	123.531 0.619	498.06 2.40 (2.98)	91.33	25.8
1150	3265.53 31.97	0.038 0.000	0.020 0.001	123.522 0.618	496.24 2.41 (2.98)	90.95	28
1165	3214.46 43.26	0.039 0.000	0.020 0.001	124.529 0.623	499.08 2.45 (3.02)	90.81	30.3
1180	3075.48 33.07	0.040 0.000	0.020 0.001	123.509 0.618	493.52 2.42 (2.98)	90.39	32
1195	3155.50 31.88	0.039 0.000	0.021 0.001	123.530 0.619	494.76 2.42 (2.98)	90.64	34
1210	3547.54 45.51	0.035 0.000	0.022 0.001	122.522 0.613	496.13 2.40 (2.98)	91.67	36.1
1225	3720.41 41.70	0.033 0.000	0.022 0.001	122.529 0.613	497.99 2.39 (2.97)	92.06	38.1
1240	4387.77 49.89	0.028 0.000	0.020 0.001	123.558 0.618	507.37 2.39 (2.98)	93.27	40.3
1255	5030.01 131.66	0.025 0.001	0.023 0.003	124.579 0.624	515.12 2.49 (3.07)	94.13	42.8
1275	5142.59 112.09	0.024 0.001	0.016 0.002	123.561 0.709	512.06 2.77 (3.30)	94.25	46.9
1290	5392.71 145.52	0.025 0.001	0.013 0.002	134.727 0.674	553.25 2.62 (3.25)	94.52	50.2
1305	4926.41 126.31	0.027 0.001	0.013 0.002	134.722 0.674	550.61 2.63 (3.25)	94	54.6
1320	4730.83 125.73	0.029 0.001	0.012 0.002	135.637 0.690	552.58 2.71 (3.32)	93.75	60
1335	3275.61 59.64	0.043 0.001	0.016 0.003	139.702 0.710	552.33 2.77 (3.38)	90.98	65.5
1350	3585.60 88.82	0.039 0.001	0.013 0.003	138.474 0.709	552.19 2.84 (3.43)	91.76	70.6
1365	3392.30 48.69	0.041 0.001	0.010 0.002	139.787 0.700	554.24 2.68 (3.30)	91.29	75.7
1380	3173.83 34.83	0.044 0.000	0.011 0.001	139.775 0.699	551.07 2.65 (3.27)	90.69	83.2
1395	2731.04 32.68	0.052 0.001	0.011 0.002	140.793 0.704	546.56 2.71 (3.31)	89.18	89.9

Appendix 1(c). (Contd.)

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
1410	2675.80	0.053	0.010	142.829	552.17	88.96	95.2
	29.28	0.000	0.002	0.714	2.73 (3.33)		
1430	2509.75	0.058	0.015	144.852	554.94	88.23	98
	28.28	0.001	0.002	0.728	2.78 (3.39)		
1445	2496.31	0.060	0.010	150.014	571.53	88.16	99.4
	25.05	0.000	0.001	0.757	2.85 (3.47)		
1500	2663.60	0.056	-0.007	150.119	575.99	88.91	100
	55.11	0.001	0.001	0.828	3.26 (3.82)		
Total	2636.44	0.052	0.018	136.620	530.52	88.79	100
	8.26	0.000	0.000	0.145	0.57 (1.94)		

Appendix 1(d). Argon isotopic composition and apparent ages of sample **Sind 08P** (Rhyolite Alkali Feldspar phenocryst) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . The data are interference, decay and mass fractionation corrected. J value is 0.002619 ± 0.000011 .

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
650	389.15	0.632	0.284	245.826	259.84	24.06	1.3
	8.60	0.008	0.009	3.662	17.76 (17.79)		
750	2741.48	0.049	0.165	133.637	490.17	89.22	7.5
	84.92	0.001	0.005	1.073	4.16 (4.56)		
810	3557.69	0.037	0.185	130.593	492.03	91.69	13.4
	143.89	0.001	0.004	0.924	3.66 (4.11)		
835	9050.98	0.014	0.196	124.516	494.57	96.74	19.3
	545.95	0.001	0.004	0.625	2.40 (3.05)		
920	4207.36	0.031	0.077	128.622	491.41	92.98	23.7
	136.78	0.001	0.003	0.678	2.64 (3.24)		
965	10393.60	0.012	0.032	123.560	493.04	97.16	29.3
	752.95	0.001	0.002	0.618	2.40 (3.04)		
980	10784.70	0.011	0.034	123.539	493.43	97.26	32.4
	614.89	0.001	0.002	0.618	2.32 (2.98)		
1000	10888.10	0.011	0.023	122.518	489.97	97.29	42.2
	216.71	0.000	0.001	0.613	2.21 (2.89)		
1030	8435.19	0.015	0.020	123.493	489.87	96.5	46.1
	156.19	0.000	0.001	0.618	2.24 (2.91)		
1070	8304.53	0.015	0.020	124.501	493.13	96.44	50.1
	210.73	0.000	0.002	0.623	2.27 (2.94)		
1105	9085.21	0.014	0.020	123.460	490.87	96.75	53.2
	190.26	0.000	0.001	0.618	2.24 (2.91)		
1150	9914.57	0.012	0.027	122.502	488.74	97.02	58.9
	216.82	0.000	0.001	0.614	2.22 (2.90)		
1190	14145.00	0.009	0.025	121.424	488.87	97.91	61.1
	878.83	0.001	0.002	0.609	2.26 (2.93)		
1300	14174.50	0.009	0.030	121.480	489.09	97.92	69.9
	882.38	0.001	0.002	0.608	2.26 (2.93)		
1325	6883.98	0.019	0.027	130.599	510.73	95.71	78.7
	196.57	0.001	0.003	0.653	2.39 (3.07)		
1340	12944.80	0.010	0.025	128.445	512.58	97.72	80.4
	1064.21	0.001	0.003	0.649	2.45 (3.13)		
1350	14065.80	0.009	0.010	131.537	524.12	97.9	82.8
	421.22	0.000	0.001	0.661	2.35 (3.07)		
1400	11523.80	0.012	0.019	133.581	529.00	97.44	87.1
	689.50	0.001	0.002	0.670	2.46 (3.17)		
1440	9612.28	0.014	0.038	136.653	537.08	96.93	95.8
	573.79	0.001	0.003	0.684	2.55 (3.25)		

Appendix 1(d). (Contd.)

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
1460	9198.79	0.016	0.028	147.659	573.41	96.79	99.1
	312.62	0.001	0.002	0.746	2.62 (3.38)		
1510	15072.60	0.011	0.012	163.166	631.07	98.04	100
	1826.67	0.001	0.001	4.631	15.46 (15.63)		
Total	5071.55	0.026	0.060	129.781	500.85	94.17	100
	43.28	0.000	0.001	0.183	0.69 (2.02)		

Appendix 1(e). Argon isotopic composition and apparent ages of sample **Sind 11P** (Feldspar Porphyry Dyke Alkali Feldspar phenocryst) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . The data are interference, decay and mass fractionation corrected. J value is 0.002853 ± 0.000011 .

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
750	368.78	0.094	6.170	33.616	34.24	19.87	1.4
	8.62	0.002	0.049	0.266	2.82 (2.82)		
800	563.87	0.086	5.482	47.177	112.56	47.59	3.5
	19.49	0.001	0.011	0.509	2.76 (2.79)		
840	1132.71	0.058	2.327	64.006	228.78	73.91	5.4
	21.13	0.001	0.012	0.525	2.65 (2.78)		
860	1765.23	0.054	2.244	93.131	361.10	83.26	6.9
	21.60	0.001	0.016	0.466	2.06 (2.44)		
880	1815.33	0.059	1.980	104.863	403.76	83.72	8.5
	20.91	0.000	0.024	0.524	2.23 (2.66)		
900	1652.99	0.063	2.389	102.772	389.87	82.12	9.7
	24.46	0.001	0.022	0.514	2.27 (2.66)		
930	1737.15	0.060	2.818	101.335	388.76	82.99	11
	23.53	0.001	0.010	0.507	2.24 (2.64)		
960	1997.27	0.054	2.537	104.987	410.80	85.2	12.5
	26.82	0.001	0.028	0.525	2.26 (2.7)		
990	1924.75	0.054	2.652	101.830	397.41	84.65	14
	23.25	0.000	0.017	0.509	2.17 (2.6)		
1020	839.25	0.130	3.364	107.375	327.47	64.79	15.4
	7.72	0.000	0.055	0.537	2.38 (2.66)		
1060	2311.66	0.039	2.414	87.104	354.51	87.22	16.4
	53.88	0.001	0.037	0.436	1.95 (2.33)		
1090	3032.09	0.024	1.087	72.280	308.07	90.25	19.5
	53.54	0.000	0.031	0.361	1.59 (1.95)		
1110	3452.04	0.022	0.817	75.777	325.51	91.44	23
	91.67	0.001	0.056	0.379	1.75 (2.12)		
1120	3613.67	0.028	1.135	98.776	415.37	91.82	25
	99.70	0.000	0.037	0.494	2.10 (2.57)		
1130	3354.40	0.030	1.210	99.989	417.37	91.19	26.9
	75.41	0.000	0.021	0.500	2.11 (2.58)		
1140	4002.00	0.022	0.777	86.627	371.92	92.62	30.6
	74.48	0.000	0.011	1.070	4.49 (4.68)		
1160	4017.07	0.024	0.801	93.375	398.02	92.64	34.4
	269.37	0.000	0.023	0.826	3.43 (3.72)		
1190	4380.29	0.024	1.095	103.071	437.39	93.25	37.5
	75.84	0.000	0.031	0.515	2.09 (2.61)		
1200	4660.38	0.022	0.561	102.484	436.65	93.66	40.8
	156.58	0.000	0.004	0.512	2.07 (2.59)		
1210	4229.81	0.024	0.637	99.879	424.17	93.01	43.8
	161.48	0.000	0.008	0.499	2.04 (2.54)		
1220	3936.50	0.031	1.215	120.078	496.85	92.49	45.6
	133.20	0.001	0.031	0.600	2.42 (2.98)		

Appendix 1(e). (*Contd.*)

Temp.	Ar-40/Ar-36 $\pm 2\sigma$	Ar-36/Ar-39 $\pm 2\sigma$	Ar-37/Ar-39 $\pm 2\sigma$	Ar-40/Ar-39 $\pm 2\sigma$	App. age (MY) $\pm 2\sigma$	% 40*	% Cum Ar-39
1230	3883.99	0.032	1.047	121.433	501.19	92.39	47.1
	106.93	0.000	0.005	0.607	2.40 (2.97)		
1240	4044.77	0.031	0.755	122.459	506.20	92.69	48.4
	168.90	0.001	0.005	0.612	2.470 (3.03)		
1250	3735.51	0.033	0.771	120.143	494.99	92.09	49.9
	270.59	0.001	0.011	0.601	2.54 (3.07)		
1260	4050.01	0.030	0.746	119.624	495.99	92.7	51.6
	201.30	0.000	0.007	0.598	2.39 (2.95)		
1275	4092.64	0.030	0.627	121.435	502.85	92.78	53.1
	333.94	0.000	0.004	0.607	2.40 (2.97)		
1290	3855.89	0.032	0.680	120.120	496.03	92.34	54.7
	225.94	0.000	0.007	0.601	2.39 (2.95)		
1305	4311.01	0.028	0.533	118.969	495.57	93.15	56.6
	108.01	0.000	0.005	0.595	2.35 (2.92)		
1325	4512.39	0.027	0.437	120.500	502.54	93.45	58.2
	296.75	0.000	0.005	0.603	2.38 (2.95)		
1340	4077.98	0.030	0.593	119.985	497.47	92.75	59.8
	286.67	0.000	0.004	0.600	2.37 (2.94)		
1355	3550.21	0.035	0.400	123.439	504.68	91.68	60.4
	110.69	0.001	0.006	0.617	2.59 (3.13)		
1380	4774.77	0.026	0.723	120.248	503.43	93.81	61.9
	310.65	0.000	0.011	0.601	2.39 (2.97)		
1410	6266.31	0.019	0.021	117.072	498.23	95.28	64.9
	93.96	0.000	0.001	0.585	2.29 (2.88)		
1440	6782.36	0.017	0.022	115.894	495.47	95.64	70.7
	67.83	0.000	0.000	0.579	2.26 (2.85)		
1455	6967.86	0.017	0.064	117.019	500.22	95.76	75.9
	75.68	0.000	0.001	0.585	2.28 (2.87)		
1465	4938.77	0.024	0.370	116.695	491.19	94.02	80.4
	89.85	0.000	0.017	0.583	2.30 (2.87)		
1475	5927.91	0.020	0.230	116.624	495.43	95.02	84.5
	156.47	0.000	0.007	0.583	2.29 (2.87)		
1485	3826.07	0.034	0.925	128.779	526.85	92.28	85.1
	152.76	0.001	0.019	0.644	2.82 (3.36)		
1500	7853.60	0.017	0.149	129.231	547.63	96.24	88.8
	420.64	0.000	0.025	0.646	2.46 (3.10)		
1515	7245.64	0.018	0.121	127.670	540.37	95.92	94.8
	125.68	0.000	0.001	0.638	2.44 (3.07)		
1525	3412.89	0.041	1.044	138.770	557.11	91.34	95.3
	245.68	0.001	0.042	0.694	2.77 (3.37)		
1555	5021.72	0.030	0.497	148.609	605.72	94.12	96.4
	152.15	0.000	0.006	0.743	2.76 (3.44)		
1580	6298.68	0.024	0.260	151.887	623.52	95.31	98.3
	215.78	0.000	0.005	0.759	2.79 (3.50)		
1600	3576.19	0.043	0.460	151.367	602.00	91.74	100
	80.94	0.000	0.005	0.757	2.83 (3.49)		
Total	3512.69	0.031	0.969	108.008	448.64	91.59	100
	19.01	0.000	0.003	0.108	0.43 (1.64)		

References

- Ahmad T, Dragusanu V and Tanaka T 2008 Provenance of Proterozoic basal Aravalli mafic volcanic rocks from Rajasthan, northwestern India: Nd isotope evidence for enriched mantle reservoirs; *Precamb. Res.* **162** 150–159.
- Bartlett J M, Harris N B W, Hawkesworth C J and Santosh M 1996 New isotope constraints on the crustal evolution of south India and Pan-African granulite metamorphism; *Geol. Soc. India Memoir* **34** 391–397.
- Bhushan S K and Chandrasekaran V 2002 Geology and geochemistry of the magmatic rocks of the Malani igneous suite and the Tertiary volcanic province of western Rajasthan; *Geol. Surv. India Memoir* **126** 179p.
- Bhutani R, Pande K and Venkatesan T R 2004 Tectono-thermal evolution of India-Asia collision zone based on ^{40}Ar – ^{39}Ar thermochronology in Ladakh, India; In: *Magmatism in India through Time* (eds) Sheth H C and Pande K; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **113** 737–754.
- Biswal T K 1988 Polyphase deformation in Delhi rocks, SE of Amirgad, Banaskantha district of Gujarat; In: *Precambrian of the Aravalli Mountain* (ed.) Roy A B; *Geol. Soc. India Memoir* **7** 267–278.
- Chore S A and Mohanty M 1998 Stratigraphy and tectonic settings of the Trans-Aravalli Neoproterozoic sequences in Rajasthan; *J. Geol. Soc. India* **51** 57–68.
- Choudhary A K, Gopalan K and Sastry A C 1984 Present status of the geochronology of the Precambrian rocks of Rajasthan; *Tectonophysics* **105** 131–140.
- Choudhary A K, Harris N B W, van Calsteren P and Hawkesworth C J 1992 Pan-African charnockite formation in Kerala, south India; *Geol. Mag.* **129** 257–264.
- Collins A S and Pisarevsky S A 2005 Amalgamating eastern Gondwana: The evolution of the circum-Indian orogens; *Earth-Sci. Rev.* **71** 229–270.
- Coulson A L 1933 The Geology of Sirohi State, Rajputana; *Geol. Surv. India Memoir* **63** 166p.
- Crawford A R 1970 The Precambrian geochemistry of Rajasthan and Bundelkhand, northern India; *Can. J. Earth Sci.* **7** 91–110.
- Crawford A R and Compston W 1970 The age of the Vindhyan system of peninsular India; *Quart. J. Geol. Soc. London* **125** 351–372.
- De Wall H and Pandit M K 2007 Cryptic fabrics in epiblasts of the Sindreth Group: Evidence for Late Neoproterozoic deformation in the western foreland of the Delhi fold belt, northwest India; *Beringeria* **37** 33–40.
- De Wall H, Schöbel S, Pandit M K, Sharma K K and Just J 2010 A record of ductile syn-intrusional fabrics to post-solidification cataclasis: Magnetic fabric analysis of Neoproterozoic Mirpur and Mt. Abu granitoids, NW India; *J. Geol. Soc. India* **75** 239–253.
- De Wall H, Pandit M K, Dotzler R and Just J 2012 Cryogenian transpression and granite intrusion along the western margin of Rodinia (Mt. Abu region): Magnetic fabric and geochemical inferences on Neoproterozoic geodynamics of the NW Indian block; *Tectonophysics* **554–557** 143–158.
- Dhar S, Frei R, Kramers J D, Nägler T F and Kochhar N 1996 Sr, Pb, Nd isotope studies and their bearing on the petrogenesis of the Jalore and Siwana complexes, Rajasthan, India; *J. Geol. Soc. India* **48** 151–160.
- Garzanti E, Casnedi R and Jadoul F 1986 Sedimentary evidence of a Cambrio–Ordovician orogenic event in the NW Himalaya; *Sedim. Geol.* **48** 237–265.
- Ghosh S, Chakraborty S, Bhalla J K, Paul D K, Sarkar A, Bishui P K and Gupta S N 1991 Geochronology and geochemistry of granite plutons from east Khasi hills, Meghalaya; *J. Geol. Soc. India* **37** 331–342.
- Gopalan K, Macdougall J D, Roy A B and Murali A V 1990 Sm–Nd evidence for 3.3 Ga old rocks in Rajasthan; *Precamb. Res.* **48** 287–297.
- Gregory L C, Meert J G, Bingen B, Pandit M K and Torsvik T H 2009 Paleomagnetism and geochronology of the Malani igneous suite, northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana; *Precamb. Res.* **170** 13–26.
- Harrison T M 1981 Diffusion of ^{40}Ar in hornblende; *Contrib. Mineral. Petrol.* **78** 324–331.
- Hoffman P F, Kaufman A J, Galen P H and Schrag D P 1998 A Neoproterozoic snowball Earth; *Science* **281** 1342–1346.
- Islam R, Upadhyay R, Ahmad T, Thakur V C and Sinha A K 1999 Pan-African magmatism and sedimentation in NW Himalayas; *Gondwana Res.* **2** 263–270.
- Just J, Schulz B, De Wall H, Jourdan F and Pandit M K 2011 Monazite CHIME/EPMA dating of Erinpura granitoid deformation: Implications for Neoproterozoic tectono-thermal evolution of NW India; *Gondwana Res.* **19** 402–412.
- Khan T, Murata M, Rehman H U, Zafar M and Ozawa H 2012 Nagarparker granites showing Rodinia remnants in the southeastern part of Pakistan; *J. Asian Earth Sci.* **59** 39–51.
- Kochhar N, Pande K and Gopalan K 1985 Rb/Sr geochronology of Tusham igneous complex, Bhiwani, India; *J. Geol. Soc. India* **26** 216–219.
- Kröner A, Hegner E, Collins A, Windley B F, Brewer T S, Razakamanana T and Pidgeon R T 2000 Age and magmatic history of the Antananarivo block, central Madagascar, as derived from zircon geochronology and Nd isotopic systematics; *Am. J. Sci.* **300** 251–288.
- Ludwig K R 2012 Isoplot/Ex, v. 3.75, Berkeley Geochronol. Center, Spec. Publ. **5**.
- Malone S J, Meert J G, Banerjee D M, Pandit M K, Tamrat E, Kamenov G D, Pradhan V R and Sohl L E 2008 Palaeomagnetism and detrital zircon geochronology of the Upper Vindhyan sequence, Son valley and Rajasthan, India: A ca. 1000 Ma closure age of the Purana basins?; *Precamb. Res.* **164** 137–159.
- McDougall I and Harrison T M 1999 *Geochronology and Thermochronology by the $^{40}\text{Ar}/^{39}\text{Ar}$ Method*; Oxford Univ. Press, 269p.
- McQuarrie N, Long S P, Tobgay T, Nesbit J N, Gehrels G and Ducea M N 2013 Documenting basin scale, geometry and provenance through detrital geochemical data: Lessons from the Neoproterozoic to Ordovician Lesser, Greater, and Tethyan Himalayan strata of Bhutan; *Gondwana Res.* **23** 1491–1510.
- Meert J G 2003 A synopsis of events related to the assembly of eastern Gondwana; *Tectonophysics* **362** 1–40.
- Meert J G and Lieberman B S 2008 The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran–Cambrian radiation; *Gondwana Res.* **14** 5–21.
- Meert J G and Van der Voo R 1997 The assembly of Gondwana 800–550 Ma; *J. Geodyn.* **23** 223–235.
- Meert J G, Van der Voo R and Ayub S 1995 Paleomagnetic investigation of the Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of Gondwana; *Precamb. Res.* **74** 225–244.

- Meert J G, Pandit M K, Pradhan V R, Banks J C, Sirianni R, Stroud M, Newstead B and Gifford J 2010 The Precambrian tectonic evolution of India: A 3.0 billion year odyssey; *J. Asian Earth Sci.* **39** 483–515.
- Mehta P K 1977 Rb–Sr geochronology of the Kulu-Manali belt – Its implications for the Himalayan tectogenesis; *Geol. Rund.* **66** 156–175.
- Mezger K and Cosca M A 1999 The thermal history of the Eastern Ghats belt (India) as revealed by U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of metamorphic and magmatic minerals: Implications for the SWEAT correlation; *Precamb. Res.* **94** 251–271.
- Pandit M K, de Wall H, Daxberger H, Just J, Bestmann M and Sharma K K 2011 Mafic rocks from Erinpura gneiss terrane in the Sirohi region: Possible ocean-floor remnants in the foreland of the Delhi fold belt, NW India; *J. Earth Syst. Sci.* **120** 627–641.
- Pankhurst R J, Moorbath S, Rex D C and Turner G 1973 Mineral age patterns in ca. 3700 my old rocks from west Greenland; *Earth Planet. Sci. Lett.* **20** 157–170.
- Paquette J-L and Nédélec A 1998 A new insight into Pan-African tectonics in the east–west Gondwana collision zone by U–Pb zircon dating of granites from central Madagascar; *Earth Planet. Sci. Lett.* **155** 45–56.
- Phillips D and Onstotte T C 1986 Application of $^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$ correlation diagram to the $^{40}\text{Ar}/^{39}\text{Ar}$ spectra of phlogopites from southern African kimberlites; *Geophys. Res. Lett.* **13** 689–692.
- Purohit R, Papineau D, Kröner A, Sharma K K and Roy A B 2012 Carbon isotope geochemistry and geochronological constraints of the Neoproterozoic Sirohi Group from northwest India; *Precamb. Res.* **220–221** 80–90.
- Rao D C V, Santosh M and Won K S 2012 Cryogenic volcanic arc in the NW Indian shield: Zircon SHRIMP U–Pb geochronology of felsic tuffs and implications for Gondwana assembly; *Gondwana Res.* **22** 36–53.
- Rathore S S 1994 *Geochronological Studies of Malani Volcanic and Associated Igneous Rocks of Southwest Rajasthan, India: Implications to Crustal Evolution*; Unpubl. Ph.D. thesis, Maharaja Sayajirao Univ., Vadodara, 175p.
- Rathore S S, Venkatesan T R and Srivastava R K 1996 Rb–Sr and Ar–Ar systematics of Malani volcanic rocks of southwest Rajasthan: Evidence for a younger post-crystallization thermal event; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **115** 131–141.
- Rathore S S, Venkatesan T R and Srivastava R K 1999 Rb–Sr isotope dating of Neoproterozoic (Malani Group) magmatism from south-west Rajasthan, India: Evidence of younger Pan-African thermal event from ^{40}Ar – ^{39}Ar studies; *Gondwana Res.* **2** 271–281.
- Ray J S 2006 Age of the Vindhyan Supergroup: A review of recent findings; *J. Earth Syst. Sci.* **115** 149–160.
- Renne P R, Swisher C C, Deino A L, Karner D B, Owens T L and DePaolo D J 1998 Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating; *Chem. Geol.* **145** 117–152.
- Roddick J C, Cliff R A and Rex D C 1980 The evolution of excess argon in alpine biotites – a $^{40}\text{Ar}/^{39}\text{Ar}$ analysis; *Earth Planet. Sci. Lett.* **48** 185–208.
- Roy A B 1988 Stratigraphic and tectonic framework of the Aravalli mountain range; In: *Precambrian of the Aravalli Mountain* (ed.) Roy A B; *Geol. Soc. India Memoir* **7** 3–31.
- Roy A B 1990 Evolution of the Precambrian crust of the Aravalli mountain range; In: *Precambrian Continental Crust and its Economic Resources* (ed.) Naqvi S M; *Developments in Precambrian Geology*, Elsevier, pp. 327–348.
- Roy A B and Jakhar S R (eds) 2002 *Geology of Rajasthan (Northwest India): Precambrian to Recent*; Scientific Publ., Jodhpur, 421p.
- Roy A B and Sharma K K 1999 Geology of the region around Sirohi town, western Rajasthan: Story of Neoproterozoic evolution of the Trans-Aravalli crust; In: *Geological Evolution of Western Rajasthan* (ed.) Paliwal B S; Scientific Publ., Jodhpur, pp. 19–33.
- Roy A B, Kröner A, Rathore S, Laul V and Purohit R 2012 Tectono-metamorphic and geochronologic studies from Sandmata Complex, northwest Indian shield: Implications on exhumation of Late Palaeoproterozoic granulites in an Archaean–early Palaeoproterozoic granite-gneiss terrain; *J. Geol. Soc. India* **79** 323–334.
- Sen A 2012 ^{40}Ar – ^{39}Ar Geochronology and Geochemistry of Sindreth and Tavidar Volcanics of Southern Rajasthan; Unpubl. Ph.D. thesis, Indian Institute of Technology Bombay, 166p.
- Sen A, Pande K, Hegner E, Sharma K K, Dayal A M, Sheth H C and Mistry H 2012 Deccan volcanism in Rajasthan: ^{40}Ar – ^{39}Ar geochronology and geochemistry of the Tavidar volcanic suite; *J. Asian Earth Sci.* **59** 127–140.
- Sharma K K 1996 *Stratigraphy, Structure and Tectonic Evolution of the Metasediments and Associated Rocks of the Sirohi Region*; Unpubl. Ph.D. thesis, M. L. Sukhadia Univ., Udaipur, 103p.
- Sharma K K 2004 The Neoproterozoic Malani magmatism of the northwestern Indian shield: Implications for crust-building processes; In: *Magmatism in India through Time* (eds) Sheth H C and Pande K; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **113** 795–807.
- Sharma K K 2005 Malani magmatism: An extensional lithospheric tectonic origin; In: *Plates, Plumes, and Paradigms* (eds) Foulger G R, Natland J H, Presnall D C and Anderson D L; *Geol. Soc. Am. Spec. Pap.* **388** 463–476.
- Shaw R K, Arima M, Kagami H, Fanning C M, Shiraiashi K and Motoyoshi Y 1997 Proterozoic events in the Eastern Ghats granulite belt, India: Evidence from Rb–Sr, Sm–Nd systematics and SHRIMP dating; *J. Geol.* **105** 645–656.
- Snee L W 2002 Argon thermochronology of mineral deposits – A review of analytical methods, formulations and selected applications; *U.S. Geol. Surv. Spec. Bull.* **2194**.
- Stern R J 1994 Arc assembly and continental collision in the Neoproterozoic East Africa orogen: Implications of the consolidation of Gondwanaland; *Ann. Rev. Earth Planet. Sci.* **22** 319–351.
- Torsvik T H, Carter L M, Ashwal L D, Bhushan S K, Pandit M K and Jamtveit B 2001 Rodinia refined or obscured: Palaeomagnetism of the Malani Igneous Suite (NW India); *Precamb. Res.* **108** 319–333.
- Trivedi J R, Gopalan K and Valdiya K S 1984 Rb–Sr ages of granitic rocks within the Lesser Himalayan nappes, Kumaon, India; *J. Geol. Soc. India* **25** 451–464.
- Ueda K, Jacobs J, Thomas R J, Kosler J, Horstwood M S A, Wartho J-A, Jourdan F, Emmel B and Matola R 2012 Post-collisional high-grade metamorphism, orogenic collapse, and differential cooling of the East African orogen of northeast Mozambique; *J. Geol.* **120** 507–530.
- Van Lente B, Ashwal L D, Pandit M K, Bowring S A and Torsvik T H 2009 Neoproterozoic hydrothermally altered basaltic rocks from Rajasthan, northwest India: Implications for late Precambrian tectonic evolution of the Aravalli Craton; *Precamb. Res.* **170** 202–222.

- Wiedenbeck M, Goswami J N and Roy A B 1996 Stabilisation of the Aravalli craton of northwestern India at 2.5 Ga: An ion probe zircon study; *Chem. Geol.* **129** 325–340.
- Windley B F, Razafiniparany A, Razakamanana T and Ackermann D 1994 Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: A review and reappraisal; *Geol. Rund.* **83** 642–659.
- Yoshida M and Upreti B N 2006 Neoproterozoic India within East Gondwana: Constraints from recent geochronologic data from Himalaya; *Gondwana Res.* **10** 349–356.
- Zeitler P K 1987 Argon diffusion in partially degassed alkaline feldspar: Insights from $^{40}\text{Ar}/^{39}\text{Ar}$ analysis; *Chem. Geol.* **65** 167–181.

MS received 26 December 2012; revised 8 May 2013; accepted 16 May 2013