Tracking the migration of the Indian continent using the carbonate clumped isotope technique on Phanerozoic soil carbonates

Prosenjit Ghosh1,2, Mikhail V. Vasiliev2, Parthasarathi Ghosh3, Soumen Sarkar3, Sampa Ghosh3, Keita Yamada4, Yuichiro Ueno5,6, Naohiro Yoshida4,6 & Christopher J. Poulsen7

Approximately 140 million years ago, the Indian plate separated from Gondwana and migrated by almost 90° latitude to its current location, forming the Himalayan-Tibetan system. Large discrepancies exist in the rate of migration of Indian plate during Phanerozoic. Here we describe a new approach to paleo-latitudinal reconstruction based on simultaneous determination of carbonate formation temperature and δ18O of soil carbonates, constrained by the abundances of 13C-18O bonds in palaeosol carbonates. Assuming that the palaeosol carbonates have a strong relationship with the composition of the meteoric water, δ18O carbonate of palaeosol can constrain paleo-latitudinal position. Weighted mean annual rainfall δ18O water values measured at several stations across the southern latitudes are used to derive a polynomial equation: δ18Ow = −0.006 × (LAT)2 − 0.294 × (LAT) − 5.29 which is used for latitudinal reconstruction. We use this approach to show the northward migration of the Indian plate from 46.8 ± 5.8°S during the Permian (269 M.y.) to 30 ± 11°S during the Triassic (248 M.y.), 14.7 ± 8.7°S during the early Cretaceous (135 M.y.), and 28 ± 8.8°S during the late Cretaceous (68 M.y.). Soil carbonate δ18O provides an alternative method for tracing the latitudinal position of Indian plate in the past and the estimates are consistent with the paleo-magnetic records which document the position of Indian plate prior to 135 ± 3 M.y.

Combined evidence from geomorphology, tomographic images, geochronology, paleontology and lithological indicators provide evidence for the palaeo-latitudinal position of the Indian plate as it was ripped from the Gondwana supercontinent and drifted northward1-3. However, the strongest evidence comes from the reconstruction of linear magnetic anomalies recovered from sub-aerial flood basalts deposited on continental-rift and sedimentary packets, which preserve information about the paleo-magnetic pole together with the occurrence of climate-sensitive litho-units like coals, evaporates, bauxites and tillites in the sedimentary successions1-4. These paleo-magnetic records disagree in the paleo-position of India during the late Paleozoic and Mesozoic time by up to 30° latitude. Reconstructions using this method involve detecting the paleo-magnetic pole from the orientation of the magnetic minerals present in the lava flows. Alternative methods to trace palaeo-latitudinal position using stable isotope techniques5 suffer from several limitations including diagenetic imprinting, poor understanding of soil temperatures and the influence of evaporation. To refine this technique, we used clumped isotope thermometry to estimate the temperature and isotopic composition of soil water, which is derived primarily measuring the δ18O of carbonates6. Studies have shown that soil carbonates formed at different latitudes vary in their meteoric water composition7. Ancient soils (paleosols) preserve a record of meteoric water isotopic compositions and therefore can be used to trace the latitudinal position during sedimentation. However, the availability of soil carbonates is an important constraint on this method. In general, soil carbonates are found only in arid to sub-humid

1Centre for Earth Sciences, Indian Institute of Sciences, Bangalore, 560012, India. 2Divecha Centre for Climate Change, Indian Institute of Science, Bangalore, 560012. 3Geological Studies Unit, Indian Statistical Institute, 203, B.T. Road, Kolkata 700 108, India. 4Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, 226-8502, Japan. 5Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan. 6Earth-Life Science Institute, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan. 7Dept. of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI 48109-1005. Correspondence and requests for materials should be addressed to P.G. (email: pghosh@ceas.iisc.ernet.in)

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Table 1. Stable isotope and clumped isotope composition of Satpura palaeosol carbonates with details about their stratigraphy, temperature. The Δ47, calibrated in CDES scale correction (Yoshida et al., 2013).

| Age M. y. | Age M. y. | Δδ13C (‰) | T (°C) | δ18O (‰)VSMOW | δ18Owater (‰) | Δ47 prep (‰)δ=SMOW | MAATa | Latt. Estb |
|-----------|-----------|------------|--------|----------------|---------------|----------------------|-------|-----------|
| Modern India* | 0.66 ± 0.01 | 36.2 ± 2(7) | -1.6 | -5.8 | -3.7 | 22 | 34°N ± 1 |
| Lameta | 68 ± 4 | 0.65 ± 0.04 | 39.0 ± 8(13) | -10.0 | -8.2 | -5.7 | 25 | 40°±5* |
| Bagra | 135 ± 14 | 0.67 ± 0.10 | 39.7 ± 6(8) | -6.4 | -5.0 | -2.3 | 26 | 30°S ± 5 |
| Denwa | 243 ± 3 | 0.71 ± 0.04 | 25.2 ± 8(13) | -8.1 | -5.7 | -5.8 | 8 | 40°S ± 6 |
| Ranchmari | 248 ± 4 | 0.65 ± 0.12 | 20.3 ± 7(6) | -8.7 | -4.9 | -6.0 | 3 | 41°S ± 6 |
| Motur | 269 ± 4 | 0.62 ± 0.09 | 34.1 ± 2(4) | -6.8 | -12.6 | -10.5 | 19 | 53°S ± 1 |

climatic conditions1,2 in relatively dry soils where C3 type grasses or mixed grasses and shrubs are the dominant vegetation. The Satpura Basin, located in Central India, has an especially well-preserved record of soil carbonates. Sedimentary sequences comprised of packets of soil carbonate were deposited along the palaeo channel of the present day Narmada River while the Indian plate drifted from its position in the Southern Hemisphere8,9. These sedimentary sequences comprised of packets of soil carbonate were deposited along the palaeo channel of the present day Narmada River while the Indian plate drifted from its position in the Southern Hemisphere8,9. These factors were responsible governing the sea-climatic conditions1,2 in relatively dry soils where C3 type grasses or mixed grasses and shrubs are the dominant vegetation. The Satpura Basin, located in Central India, has an especially well-preserved record of soil carbonates. Sedimentary sequences comprised of packets of soil carbonate were deposited along the palaeo channel of the present day Narmada River while the Indian plate drifted from its position in the Southern Hemisphere8,9. These factors were responsible governing the sea-climatic conditions1,2 in relatively dry soils where C3 type grasses or mixed grasses and shrubs are the dominant vegetation. The Satpura Basin, located in Central India, has an especially well-preserved record of soil carbonates. Sedimentary sequences comprised of packets of soil carbonate were deposited along the palaeo channel of the present day Narmada River while the Indian plate drifted from its position in the Southern Hemisphere8,9. These factors were responsible governing the sea-

Clumped isotope analyses
In order to understand the temperature and fluid composition during precipitation of the soil carbonates, we analyzed clumped isotopic ratios in bulk carbonate samples. XRD analysis reveals that calcite and clays are the prominent minerals present in the samples8. The abundance of Δ47, δ13C and δ18O of carbonates from the Motur, Denwa, Ranchmari, Bagra and Lameta formations are given in Table 1 and Fig. 1. The Δ47 constrains carbonate growth temperature independent of the δ18O of waters from which they grew4. The Δ47 temperatures were then used to constrain the δ18O of water4 (i.e., because both the growth temperature and the δ18O of carbonate are known). Here we determined soil water δ18O values upon using conventional paleo-thermometry equation14 where temperature (Fig. 1e) of carbonate precipitation and δ18O of carbonate (Fig. 1b) were derived from the experimental results. This soil water δ18O value ranges between 0.25 ± 2.20 (‰, VSMOW) and −8.1 ± 2.0 (‰, VSMOW). Uncertainty or heterogeneity in the composition of carbonate is due to variability in temperature of carbonate precipitation, water, soil respiration and δ18O standard deviations from the mean and are marked in the plots (Fig. 1e) of Δ47, calcification temperature, δ13C and δ18O. The age uncertainties were established based on the bio-stratigraphy of the Motur, Ranchmari, Denwa, Bagra and Lameta formations14-19. Both surface temperature and meteoric water δ18O are grossly linked with latitude. The relationship with δ18O of meteoric water and latitude is assumed to remain similar through 250 M.y. Factor like continental configuration is expected to influence the heat transfer process and isotopic distribution across latitude. But the simulation experiment conducted with land configuration resembling Permian 250 M.y. produced a thermal mode of circulation, similar to the modern North Atlantic, supporting our argument of grossly similar or slightly different equator-to-pole temperature gradient than the modern day20. These factors were responsible governing the seasonal distribution of isotopic ratios in meteoric water across the latitudes21. However, there are evidences which support that the yearly average isotopic ratios across the latitude remain more or less similar and comparable to
modern day. Experimental evidence of comparable lighter isotopic ratios in the fresh water was detected in the carbonate precipitates from Permian and Carboniferous environment support our viewpoint22,23. We used Δ47 based temperature estimates as input parameter together with δ18O of specific soil carbonates to derive the δ18O of soil water. Considering soil water as derived from the meteoric water an additional evaporative effect was introduced. The modification of soil water composition likely varied through evaporation depending upon the latitudinal position. An enrichment factor of 2‰ and 2.5‰ are adopted for the samples with palaeo-latitudinal positions south of 50°S and north of 50°S respectively, to reflect this variation (see Table 1). The values obtained for the meteoric water (δ18Oppt) are fed into the polynomial equation for the reconstruction of the latitudinal positions and uncertainties of predicted values vary with Latitudes (Extended Data Figs 1 and 2); with higher accuracy been observed for prediction of positions at higher latitudes. The latitudinal dependence of temperature and δ18O are known from the IAEA database covering several stations across the Southern Hemisphere. Independent estimates on the pCO2 level during carbonate precipitation are established from the δ13C values of pedogenic carbonates8. To account for the influence of changes in atmospheric pCO2 on air temperature, we compare our results with those from global climate model (GCM) predictions of air temperatures and isotopes ratios in precipitation over a range of atmospheric pCO2 levels24 (Extended data Fig. 3). Although

Figure 1. Plots of carbon, oxygen isotope ratios, Δ47, temperatures of carbonate precipitation and estimated water isotopic composition with age (time of deposition) are shown. (a) Average carbon isotope ratios from replicate samples, (b) Average oxygen isotope ratios from replicate samples, and (c) Average Δ47 measured from replicate samples of soil carbonates obtained from the different strata of varying ages with error bar marking 1σ around mean values. Data from earlier work15–18 are also shown for comparison (d) Average temperature estimates for soil carbonate precipitation estimated from the measured Δ47 values by using the relationship given by Ghosh et al.14 and later revised by Dennis et al., (2012) (e) Estimated δ18O of soil water in an equilibrium condition plotted with age. Temperature and δ18O of carbonate measured in this study were used as input parameters in the oxygen isotope thermometry18 equation to obtain the values.

Figure 2. Position of the Indian plate during the Phanerozoic period is shown here while it drifted from the southern hemisphere to its present position in the northern latitude. The exact position and uncertainties of plate location are based on the palaeo-magnetic data1–4. The palaeosol samples used in this investigation were dated based on the presence of vertebrate fossils10,11,15. A paleo-latitudinal reconstruction from specific soil carbonates isotopic data involves use of empirical relationship between δ18O of meteoric water (GNIP data) and latitudes (see Extended Data Fig. 1). The δ18O of past meteoric water was estimated after taking into account evaporative fractionation at different latitudes.
estimates of meteoric water isotopic composition at varying level (2x, 4X, 8X and 12X) of atmospheric CO2. Temperatures derived using the relationship proposed by Ghosh late Triassic16–18. The fact that the Bagra Formation overlies the Denwa in Central India suggests that it is younger than late Triassic but older or equivalent to the late Jurassic-early Cretaceous (135 ± 14 M.y. ago). The age of the Denwa Formation has been taken to be around the ~35 m-thick fluvial sediments of the Lameta Formation transitional overlap the fluvial sandstone and mudstone of the Cretaceous8, Jabalpur Formation and are conformably overlain by the Tertiary Deccan trap basalts. The vertical error bar denotes the δ18O of precipitation estimates established analyzing number of samples of paleosol carbonates from specific stratigraphic horizon as described in the text. A large offset from the model results was noted for the carbonates from Bagra formation, suggesting anomalously excess evaporation during the deposition of these sediments.

the simulated values are meant for Cretaceous climate, the zonal average temperatures are reasonable for others periods (within the Paleozoic and early Mesozoic era) as well where the pCO2 concentration were within 4 to 12 times of the present day atmospheric values.

**Age assignment to the strata.** The age of the Satpura Basin paleosols are known to range from 269 to 68 M.y. ago based on the occurrence of index fossils including vertebrate fauna and diatoms. The ages have recently been redefined based on discovery of several vertebrate fossils12,13. The relative ages of the sedimentary strata were also obtained based on the stratigraphic position of the bed with respect to the strata with known ages. In both cases, the floral and faunal fossil records provided biostratigraphic age estimates to the Motur, Pachmarhi, Denwa, Bagra and Lameta formations. The age of the Talchir Formation, which hosts girty sandstone, glacial conglomerate and striations, is placed at Permo-Carboniferous (290 M.y. ago), while the Motur, Panchmarhi, Denwa and Lameta Formations were dated Early Middle Permian (269 ± 4 M.y. ago), Late Lower Middle Triassic (248 ± 4 M.y. ago), Early Middle Triassic (243 ± 3 M.y. ago) and Late Cretaceous (68 ± 4 M.y. ago) respectively12-13. In the absence of any fossil records from the Bagra Formation, several workers have contended that it might be equivalent to or younger in age than Denwa12,13,15. Since the age of the Denwa Formation is considered to be between the late Lower to the Middle Triassic18, the age of the Bagra formation has been taken to be around the late Triassic16–18. The fact that the Bagra Formation overlies the Denwa in Central India suggests that it is younger than late Triassic but older or equivalent to the late Jurassic-early Cretaceous (135 ± 14 M.y. ago)19. The Lameta Formation in Central India is located at the Lameta Ghat on the Narmada River, 15 km southwest of Jabalpur. The ~35 m-thick fluvial sediments of the Lameta Formation transitional overlap the fluvial sandstone and mudstone of the Cretaceous8, Jabalpur Formation and are conformably overlain by the Tertiary Deccan trap basalts.

**Estimation of average air temperature from calcite clumped isotopes.** Several empirical formulations have been proposed for deriving temperature (air and calcite growth temperature) from clumped isotope data subsequent to the initial paper on clumped-isotope thermometry26-27. We report here calcite precipitation temperatures derived using the relationship proposed by Ghosh et al.14 and revised recently to accommodate the absolute reference frame28. The precipitation temperatures of calcite present in the samples are 34.1 ± 2 °C for 269 M.y. ago, 20.3 ± 7 °C for 248 M.y. ago, 25.2 ± 8 °C for 243 M.y. ago, 39.7 ± 6 °C for 135 M.y. ago and 39.0 ± 8 °C for 68 M.y. ago. Clumped isotope studies on modern soil carbonates across northern latitudes provide a method to relate clumped temperature with mean annual air temperature and warmest average monthly temperatures29. Using this relationship, the mean annual air temperatures (MAAT) were derived for the past soil carbonates26 are 19 ± 2 °C for 269 M.y. ago, 3 ± 7 °C for 248 M.y. ago, 8 ± 8 °C for 243 M.y. ago, 26 ± 6 °C for 135 M.y. ago and 25 ± 8 °C for 68 M.y ago (see Extended Table 2). Similarly, warmest monthly air temperatures estimated based on the equation28 for our analysis of samples are 31 ± 2 °C for 269 M.y., 14.6 ± 7 °C for 248 M.y., 20 ± 8 °C for 243 M.y., 33.7 ± 6 °C for 135 M.y. and 36.2 ± 8 °C for 68 M.y. The majority of the temperature estimates are within several degree of modern average annual air temperature across the latitudes except for a few samples from the early Cretaceous and Permian, where the estimated temperature are slightly higher than modern day temperatures at those latitudes. It is possible that higher pCO2 condition during these time periods were responsible for the warmer temperatures recorded in our samples compared to the present day value. The samples recording lowest temperature and lightest δ18O are expected to be most pristine, while samples with anomalously high temperatures are likely preserving signature of recrystallization and burial diagenesis which happens at elevated
temperatures. In order to rule out the possibility of diffusion related process resetting the original composition, we compared clumped isotope temperature with the inferred temperature expected during deep burial (Extended Data Fig. 3).

We further compare our results with zonal average surface temperatures simulated using a GCM under a range of $p_{CO_2}$ values. The temperature values observed in our study at different latitudes are cooler than the simulated annual zonal temperatures. This discrepancy might indicate a seasonal bias to calcite precipitation. Calcite precipitation can happen during the period of water saturation or well-drained condition during a year. Studies have shown that the cold dry period with well-drained soil condition induces high soil respiration which is registered as enriched $\delta^{13}C$ values in the soil carbonates. In contrast, warm wet conditions dampen the rate of soil respiration, which is registered as lighter $\delta^{13}C$ values in the soil carbonates. A close inspection of the $\delta^{13}C$, $\delta^{18}O$ and deduced Mean Annual Air Temperature (MAAT) for the samples suggests seasonal deposition of Lameta and Bagra soil calcite (Extended Data Fig. 4). Higher rate of soil respiration, low Eh condition and low input of atmospheric $CO_2$ is inferred for Lameta soil while soil formed during Bagra deposition registered a low rate of soil respiration, high Eh condition and enhance input of atmospheric $CO_2$. Soil carbonates analyzed for other time period fall within a wide range of $\delta^{13}C$ values covering entire year with high and low soil respiration rate, variable Eh and atmospheric $CO_2$ input conditions. Furthermore, the clumped isotope temperature estimates for soil carbonates support the high $CO_2$ level predicted earlier using $\delta^{13}C$ values of soil carbonate and their organic matters.

**Latitudinal position of the Indian plate and Uncertainty.** The available paleogeographic reconstructions suggest that the Satpura Gondwana basin was positioned at 60°S in the Early Permian and moved to 30–40°S by the Middle Triassic and thus traversed through different climatic zones during this period. Existing paleomagnetic data suggest the position of the Indian plate relative to its current position (Fig. 2). Accurate positioning of the Indian plate during Phanerozoic is based upon a variety of archives; including sea-floor magnetic anomalies, geochronology and palaeo-magnetic data on flood basalt and relative position of hot spot track. At present, knowledge the exact positions (with uncertainties) of Indian plate are based on the compilation of data from various sources including the on-going PALEOMAP (http://www.scotese.com/) project. The palaeo-latitude of India is determined from global synthetic apparent polar wander paths (APWPs) which place the central Indian region at 53°S during the deposition of the Motur sediments. The average position of the Indian plate during the Triassic period was 44°S and shifted to nearly 35°S by the late Jurassic period. Finally, the Indian plate was located at 22°S during the Cretaceous period. There are several reasons not to rely on the global APWP. First, their curve extends back only to 200 M.y., whereas we are interested in motions back to the Permian. A late Permian and Triassic segment to the Besse and Courtillot reconstruction of plate movement was found to be geologically implausible and an alternative approach to validate the position of Indian plate is in high demand.

This use of stable isotope in terrestrial carbonate for predicting latitude has been successfully demonstrated in reconstructing the locations of continents in the northern hemisphere. However, in majority of these studies the predicted value of $\delta^{18}O$ in calcite as a function of latitude were likely compromised by absence of information about soil temperature, depth of soil calcite precipitation, and evaporation of soil water. Here we obtained soil temperature from $\Delta T_p$ and accommodated evaporation effect. Effect of elevation governing the isotopic composition of precipitation was considered minimal as the palaeo-elevation of the basins is unknown. However, based on sedimentary record documenting structures associated with the strata where soil carbonates were deposited it is concluded that most of the deposition was confined to a flood plain setting at elevation close to mean sea level. The $\delta^{18}O_{mow}$ values of water in equilibrium with soil carbonates varies through the section and averages $\sim\pm 8.9\%$ in the Motur Formation, $\sim\pm 4.3\%$ in the Pachmarhi Formation, $\sim\pm 4.0\%$ in the Denwa Formation, $\sim\pm 0.0\%$ in the Bagra Formation, and $\sim\pm 3.4\%$ in the Lameta Formation. Allowing corrections for the soil water $\delta^{18}O_{mow}$ values due to the effect of processes like evaporation. We translated the soil water $\delta^{18}O_{mow}$ to true meteoric water $\delta^{18}O_{mow}$ values by including a constant evaporative enrichment factor of 2% for Motur carbonates and 2.5% for rest of the carbonates from four stratigraphic levels (See Supplementary data). The soil water isotopic values resemble values for the meteoric water after correction and thus been suitably used as input values in the empirical model for predicting the latitudinal position of soil carbonates. However, uncertainties on the calculated $\delta^{18}O_{mow}$ due to error in determination of isotopic fractionation factor between water and calcite was ignored. The latitudinal position varied during the deposition of sediments across the succession and the average position are 53 ± 1°S during deposition of Motur sediments, 41 ± 6°S for the Pachmarhi sediments, 40 ± 6°S for the Denwa sediments, and 30 ± 5°S and 40 ± 5°S for the Bagra and Lameta Formations respectively. The approach is validated for the modern samples of soil carbonates from India which yielded latitude position of 34 ± 1°N as compared to the actual position of 27–31°N latitude (Table 1). Uncertainties in our estimates are within 20% of the true value (as explained in the Extended Data Fig. 2) for samples lying within 30°S latitude. Our results are consistent with previous paleo-latitudinal estimates but provide new constrains on the position in cases where limited data of APW is retrieved from the sedimentary sequences. The uncertainties in the paleo-latitudinal estimates are mainly due to the factors like scatter in the $\Delta T_p$ values and $\delta^{18}O$ of carbonates. Soil carbonates of the Lameta, and Bagra formations, being formed close to the mid latitudes, yielded large uncertainties while carbonates deposited at low latitudes, namely in the Denwa, Panchmari and Motur Formations are less uncertain in terms of their latitudinal position.

**Hydrological circulation during periods of elevated greenhouse gases level.** Ghosh et al. previously used the carbon isotopic composition of inorganic and organic remnants from the same set of palaeosol carbonates to derive $pCO_2$ in the Phanerozoic period. Our previous estimates showed that the $CO_2$ content of the atmosphere during depositional of the Motur formation was 540–890 ppmv while the concentration increased to 910–1510 ppmv during the period of deposition of soil carbonate in the Denwa formation. Similarly, the $pCO_2$
content registered analyzing the samples from Bagra formation was 1675–2775 ppmv, while pCO₂ content of atmosphere recorded analyzing the Lameta samples was 1110–1850 ppmv. These estimates are in agreement with the GEOCARB model prediction. In this study, we determine the temperature of carbonate precipitation and obtain more precise estimates of the isotopic compositions of ancient soil waters and precipitation. The estimated water isotopic compositions were used for predicting the latitudinal position for the carbonate depositions and compared with the modal GNIP data for the prediction (Fig. 3). We compare our soil water compositions with precipitation isotopic compositions simulated using the GENESIS GCM for a range of elevated atmospheric CO₂ levels (Fig. 3). The meridional variability of soil water isotopic compositions compares reasonably well with the simulated meridional variability in zonal-average precipitation, indicating that to first order ancient soil water does track paleo-latitude. The comparison also demonstrates a systematic isotopic enrichment of most meteoric waters relative to both modern observed and simulated precipitation. The meteoric δ¹⁸O values recorded in the carbonates during 269 M.y. until 135 M.y. are enriched compared to modern day average isotopic composition of precipitation across the latitude and even exceeded the simulation trend at higher pCO₂ condition.

Conclusion

The paleosol carbonates were precipitated in fluvial sediments during Permian to Cretaceous periods, coinciding with the movement of Indian landmass towards north and is overlain by the Deccan basalt on the top. The stratigraphic position of the paleosol carbonates restricted water rock interaction and late diagenetic transformation of the original signatures. Clumped isotopic analysis on these samples reveals the temperature of calcite precipitation and the oxygen isotope ratios of carbonates. We note that the clumped isotope temperatures are lower than GCM-simulated annual surface temperatures, likely indicating a seasonal bias in carbonate precipitation. The isotopes in precipitation show very good agreement with the simulated meridional distribution. Not only does this validate using soil water δ¹⁸O as a paleo-latitude proxy, it also implies that the global-scale hydrological cycle was not fundamentally different during the climates of the late Paleozoic and Mesozoic. The δ¹⁸O values derived here are more robust than the temperature values as it captures the environmental water at the time of calcite precipitation or later during the process of early diagenesis. The secondary calcites precipitated from the diagenetic water at higher temperature closely resemble the composition of environmental water. This suggests that the early diagenetic water is similar to the environmental water. This is documented in our observation. The temperature trends recorded in the sample are consistent with the model-based estimates, except for the 269 M.y. samples, which is much too warm. Also, pedogenic carbonates have a tendency of becoming increasingly enriched in δ¹⁸O at higher MAT and evaporation rates. A systematic enrichment of 0.5‰ would bring all the points in line with the model predictions. Therefore, any offset in paleo-latitude reconstruction can partly be explained by adopting a systematic isotopic enrichment. The approach of using the latitudinal variability of oxygen isotopic composition in rainfall is used here to estimate the position of Indian plate and shows great promise, especially at mid and high latitudes where isotopic gradients are greatest. This method could be further refined by simulating specific time slices in the past and comparing carbonate δ¹⁸O with simulated δ¹⁸O at specific locations. Based on the data we observe variations in the rate of drifting of Indian plate. Assuming the orientation of Indian plate remaining unchanged during its journey to the north, we can deduce the rate of movement of Indian plate with shift in the mean latitudinal position with age. Assuming 111 km correspond to a drift of 1° latitude, we estimate the rate of migration was 51 mm/year between 269 M.y. and 243 M.y., dropping to 10 mm/year during the interval between 243 M.y. ago and 135 M.y. ago.

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