New age constraints for the Proterozoic Aravalli–Delhi successions of India and their implications

N. Ryan McKenzie a,b,⁎, Nigel C. Hughes b, Paul M. Myrow c, Dhiraj M. Banerjee d, Mihir Deb d, Noah J. Planavsky e

a Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, TX 78712, USA
b Department of Earth Sciences, University of California, Riverside, CA 92521, USA
c Department of Geology, Colorado College, Colorado Springs, CO 80903, USA
d Department of Geology, Delhi University, Chhatta Marg, Delhi 110007, India
e Department of Geology and Geophysics, Yale University, New Haven, CT 06520, USA

A R T I C L E   I N F O

Article history:
Received 24 April 2013
Received in revised form 19 September 2013
Accepted 2 October 2013
Available online 12 October 2013

Keywords:
Proterozoic
Aravalli
Vindhyan
Detrital zircon
Phosphorite
Boring billion

A B S T R A C T

Proterozoic sedimentary successions of India are important archives of both the tectonic history of the Indian subcontinent and the evolution of Earth’s crustal evolution. The lack of firm age constraints on many of these stratigraphic units limits their current utility. Here, we present new detrital zircon age data from strata of the southern Aravalli–Delhi Orogenic Belt (ADOB) and the Rajasthan Vindhyan successions. The Alwar Group of the southern Delhi Supergroup yielded a large population of ~1.2 Ga detrital zircon grains, which refutes the 1.9–1.7 Ga age assertion for this unit. Detrital zircon age distributions from the southern Alwar Group differ strongly from the Alwar Group of the “North Delhi Belt”, demonstrating miscorelation between these two regions. The Jhamarkotra Formation of the Lower Aravalli Group contains a large population of 1.9–1.7 Ga detrital zircon grains. Therefore, the unit cannot be ~2.1 Ga as traditionally assumed. Age distributions of the Aravalli and Delhi supergroups are similar to those of the lower and upper Vindhyan successions, and we postulate contiguous sedimentary sources for both regions, with strata of the tectonically deformed ADOB representing the distal margin equivalents of the Vindhyan successions. Additionally, a late Paleoproterozoic age for the Jhamarkotra Formation nullifies the hypothesis that the markedly positive carbonate δ13C values in this unit are linked to the 2.3–2.0 Ga Lamangudi–Jatuli positive isotope excursion. The potential of a large late Paleoproterozoic (ca. 1.7 Ga) positive δ13C excursion contrasts with the long-held view of a prolonged period of carbon isotope stasis during the so-called ‘boring billion’.

© 2013 Published by Elsevier B.V.

1. Introduction

Thick Proterozoic sedimentary successions that cover the Indian shield are considered deposits of discrete isolated basins that are often referred to as the “Purana Basins” (Purana means ancient) (e.g., Holland, 1909; Valdiya, 1995; Chakraborty, 2006; Chakraborty et al., 2010). Modern physiographic features and differences in tectonic deformation typically define the boundaries of the so-called Purana Basins. The degree of continuity or isolation of these basins from one another during the time of sediment accumulation remains unclear. Interbasinal correlation has largely been hindered by a lack of depositional age constraints on the strata within them.

However, there are recently developed chronostratigraphic frameworks for these various successions (e.g., Patranabis-Deb et al., 2007; Bengtson et al., 2009; Malone et al., 2008; Pradhan et al., 2010; Bickford et al., 2011; McKenzie et al., 2011; Mukherjee et al., 2012; Pradhan et al., 2012). These are critical to furthering understanding of the tectonic–sedimentary evolution of the Indian subcontinent. Additionally, these successions preserve critical information about the Proterozoic evolution of the biosphere (e.g., Bengtson et al., 2009; Papineau et al., 2009, 2013). The Aravalli Supergroup, in particular, contains carbonate rocks with markedly positive carbonate δ13C values that have been linked to the ~2.3–2.1 Ga Paleoproterozoic Lamangudi–Jatuli carbonate carbon isotope excursion (Sreenivas et al., 2001; Maheshwari et al., 2002, 2010; Purohit et al., 2010). The Aravalli Supergroup has also been proposed to contain the oldest phosphorites in the rock record, which along with additional geochemical data, have been used for inferences on biogeochemical cycling following the ~2.4 Ga Great Oxidation Event (Papineau et al., 2009, 2013; Papineau, 2010).
In this study we present new U-Pb detrital zircon age data from major stratigraphic units of the southern Aravalli and Delhi supergroups and the Vindhyan successions of Rajasthan, India. These data provide new constraints that drastically revise the depositional ages of the Aravalli and Delhi supergroups. Furthermore, these new age constraints appear to redefine the significance of carbonate carbon isotope trends from Proterozoic Aravalli strata.

2. Geologic setting

2.1. Aravalli–Delhi Orogenic Belt

The roughly north–south trending Aravalli–Delhi Orogenic Belt (ADOB) of western India exceeds 700 km in length (Deb et al., 1989; Roy and Jakhkar, 2002) (Fig. 1). Two major stratigraphic units are defined in the ADOB: the lower Aravalli Supergroup and the upper Delhi Supergroup (Fig. 2). The ADOB is divided into northern and southern “belts” with strata of both the Aravalli and Delhi supergroups recognized in the southern belt, whereas all strata of the northern belt are classified as Delhi Supergroup, and thus it is commonly termed the “North Delhi Belt”. At least two major tectonothermal events are recorded in the ADOB that can be broadly defined as late Paleoproterozoic (1.9–1.6 Ga) and late Mesoproterozoic–early Neoproterozoic (1.1–0.8 Ga) in age (Deb et al., 1989, 2001; Buick et al., 2006; Bhownik et al., 2010; Meert et al., 2010).

The Aravalli Supergroup overlies the ~2.5 Ga Banded Gneiss Complex-I (BGC-I) Deb and Sarkar, 1990 (Deb et al., 1989; Wiedenbeck et al., 1996; Buick et al., 2006; Meert et al., 2010; Pradhan et al., 2010) and is divided into lower, middle and upper groups. The Lower Aravalli Group includes the basal Delwara Formation, which consists mostly of siliciclastic strata with interspersed volcanics, and the overlying carbonate-dominated Jhamarkotra Formation, which contains localized phosphorite (Banerjee, 1971; Banerjee et al., 1986). It has been suggested that the Aravalli Supergroup was deposited in a series of “sub-basins” along an active rift margin (Roy and Paliwal, 1981; Roy and Jakhkar, 2002) but, just as with the definition of the Purana Basins, the so-called “sub-basins” of the Aravalli Supergroup are defined by modern day outcrop limits and lithological facies variations, primarily the presence or absence of phosphatic stromatolites. As a result, these sub-basins have been subsequently divided into “phosphatic” and “non-phosphatic” domains (Papineau et al., 2009, 2013; Purohit et al., 2010). Their status as isolated basins during deposition has yet to be adequately verified, as there are no

ARAVALLI-DELHI OROGENIC BELT

Delhi Sgr.
Ajabgarh Gr. ———— mixed siliciclastic-carbonate
Alwar Gr. ———— siliciclastic dominated

Aravalli Sgr.
Upper Aravalli Gr. ———— siliciclastic dominated
Middle Aravalli Gr. ———— siliciclastic dominated
Lower Aravalli Gr. ———— carbonated Delwara Fm. ———— siliciclastic with interspersed mafic volcanics

VINDHYAN SUCCESSIONS

Upper Vindhyan
Bhander Gr. ———— mixed siliciclastic-carbonate
Rewa Gr. ———— siliciclastic dominated
Kaimur Gr. ———— siliciclastic dominated

Lower Vindhyan
Semri Gr. ———— mixed siliciclastic-carbonate

Fig. 2. Simplified stratigraphic nomenclature and general lithologies for strata of the Aravalli–Delhi Orogenic Belt and the Vindhyan successions (units listed in stratigraphic order), Sgr. = Supergroup; Gr. = Group; Fm. = Formation.
well-constrained synsedimentary faults or evidence for basement onlap of strata between the sub-basins. This, combined with lithostratigraphic similarities between "sub-basin" deposits throughout the region, supports arguments against the suggestion that these sedimentary units were originally laterally discontinuous or that each "sub-basin" was a separate depositional system. Furthermore, regardless of the validity of the sub-basin model, Papineau et al. (2013) used integrative data to argue for contemporaneous deposition of the Jhamarkota Formation strata throughout the region.

The Lower Aravalli Group is considered to have depositional ages from 2.1 to 1.9 Ga, although geochronologic constraints for this age range are contentious. A minimum age constraint is often inferred from a ~1.9 Ga Rb–Sr isochron for the Darwal granite that is believed to intrude the base of the Lower Aravalli Group (Choudhary et al., 1984). However, Deb and Thorpe (2004) noted a complicated contact relationship between the Darwal intrusion and basal Aravalli strata, and questioned its usefulness for providing a minimum age constraint. Ahmad et al. (2008) presented a series of whole-rock Sm–Nd model ages for ultramafic–mafic volcanic rocks in the basal Delwara Formation that ranged from 2.3 to 1.8 Ga. The wide range of calculated ages for this series of volcanic flows (±0.5 billion year interval) illustrates a problem with using these data for reliable age constraints. Sparsely Pb–Pb model ages from galena extracted from barite veins in Delwara volcanics yielded ages around 2.1–2.0 Ga, whereas the majority of Pb–Pb galena model ages from various units within the Lower Aravalli Group consistently yielded ages around 1.8–1.7 Ga (Deb et al., 1989; Deb and Thorpe, 2004). A 2.2–2.0 Ga depositional age has also been suggested for the Jhamarkota Formation based on correlation of anomalously 13C-enriched carbonate in the Jhamarkota Formation with the Lomagundi–Jatuli isotope excursion (above). However, recent age data for the Delhi Supergroup are conflicting. Strata of the North Delhi Belt are well constrained to 1.8–1.7 Ga with minimum and maximum age depositional ages provided by cutting relationship of intrusive igneous rocks and detrital zircon age data, respectively (Biju-Sekhar et al., 2003; Kaur et al., 2011), whereas rocks associated with the upper Delhi Supergroup in the southern belt may be as young as ∼1.1 Ga (Deb et al., 2001). It is also noteworthy that the Delhi Supergroup rocks of the southern belt lack ∼1.7 Ga intrusive rocks known from the North Delhi Belt, and these strata have not yielded Pb–Pb model ages older than ~1.0 Ga (Deb and Thorpe, 2004).

2.2. Vindhyan successions

The Great Boundary Fault marks the eastern limits of the ADOB and is the present structural boundary with the Vindhyan basin. The Vindhyan basin is regionally divided into the western Rajasthan and eastern Son Valley sectors (Fig. 1). Vindhyan strata are divided into lower and upper successions by a prominent unconformity, with the lower Vindhyan succession consisting of the Semri Group and the upper Vindhyan succession consisting of the Kaimur, Rewa, and Bhandar groups, in ascending order (Fig. 2). The upper part of the Semri Group is well dated at ~1.6 Ga (Rasmussen et al., 2002; Ray et al., 2002; Ray, 2006; Bgntson et al., 2009), and strata of the upper Vindhyan succession are constrained to between ~1.1 and 1.0 Ga (Gregory et al., 2006; Malone et al., 2008; McKenzie et al., 2011; Pradhani et al., 2012; Gopalan et al., 2013). Thus, the unconformity between the upper and lower Vindhyan successions represents an approximate 500 million year interval.

3. Methods

Detrital zircon geochronology has proven useful for establishing depositional age constraints on siliciclastic strata and resolving correlation problems across the Indian craton (e.g., Malone et al., 2008; McKenzie et al., 2011). In this study, new detrital zircon U–Pb age data were generated from siliciclastic rocks of the Aravalli and Delhi supergroups of the southern ADOB and Vindhyan successions of Rajasthan (Figs. 3 and 4). Individual zircon grains were separated using standard heavy mineral separation procedures and analyzed by means of laser ablation multicollector inductively coupled mass spectrometry (LA–MC–ICPMS) at the University of Arizona Laser–Chron Center (see supplementary materials for analytical details and data tables). Back-scattered electron (BSE) images of polished grain mounts were used to help target portions of zircon grains with clear growth zoning for spot analysis and to avoid inherited cores, un-zoned rims, and fractures. Sandstone samples analyzed from the Aravalli Supergroup include the basal Delwara Formation (RA10), the Jhamarkota Formation (RA5), and the Middle Aravalli Group (RA11). A Delhi Supergroup sample was analyzed from the Alwar Group (RD4). Vindhyan samples collected near Chittorgarh include the Semri (RSV1) and Kaimur groups (RVK1). Unfortunately, samples collected from the Upper Aravalli Group and the Ajabgarh Group of the upper Delhi Supergroup did not yield zircon grains.

4. Results and discussion

4.1. Revised ages for the Aravalli Supergroup

The base of the Delwara Formation sample (RA10) contains a range of Archean zircon grains with only a single concordant zircon younger than ~2.5 Ga, which yielded a 206Pb/238U age of 1709 ± 8 Ma. The Jhamarkota Formation sample (RA05) contains a large population of 1.9–1.7 Ga detrital zircon (~1772 Ma age peak) and the youngest single grain yielded a 206Pb/238U age of 1762 ± 9 Ma. A sample from the middle Aravalli group (RA11) contained a broad population of 1.8–1.6 Ga detrital zircon with abundant ~2.5 Ga grains and the single youngest zircon yielded a 206Pb/238U age of 1576 ± 7 Ma (Fig. 4).

The single 1709 ± 8 Ma grain provides a problematic age constraint for the Delwara Formation. The Delwara sample was collected less than 1 km above the depositional contact with the BGC-I basement. The large population of Archean grains was likely derived directly from proximal BGC-I rocks, and the near-absence of ~1.7 Ga grains might be the result of dilution from locally derived detritus. A similar dilution problem may exist with a sample from the Semri Group of the lower Vindhyan succession (discussed below). The possibility that the single ‘young’ 1709 ± 8 Ma grain resulted from contamination during sample processing must also be considered, although this is unlikely as grains around this particular age are not common in any sample. Alternatively, the single ‘young’ grain may represent an inaccurate age from erroneous measurement or later alteration of the grain through Pb loss or metamorphic overprinting during a ~1.7 Ga tectonothermal event (see Buick et al., 2006). Therefore, the single ~1.7 Ga grain only provides a tentative age constraint for the Delwara Formation and further investigation of this unit is required.

The presence of a large population of 1.9–1.7 Ga zircon grains in the Jhamarkota Formation nullifies assertions of 2.2–2.0 Ga depositional ages for the formation and for all overlying strata of the Aravalli Supergroup. The detrital zircon data presented here constrain only the maximum depositional age. However, Deb et al. (1989) reported numerous ~1.7 Ga Pb–Pb model ages for syn-genetic ore deposits associated with the Jhamarkota Formation that provide tentative minimum depositional age constraints for
the unit. Therefore, the Jhamarkotra Formation is interpreted to have a $\sim 1.7$ Ga depositional age. This age is further supported by a lack of younger $\sim 1.6$ Ga zircon grains that are present in the overlying Middle Aravalli Group and a lack of Mesoproterozoic grains that are common in younger strata of the ADOB and other Indian cratonic successions (e.g., Malone et al., 2008; McKenzie et al., 2011) (Fig. 4). The Aravalli region experienced considerable magmatic activity between 1.9 and 1.7 Ga (Deb et al., 2002; Biju-Sekhar et al., 2003; Buick et al., 2006; Kaur et al., 2007, 2009), with Andean-type subduction and arc magmatism postulated along the margin (Kaur et al., 2009, 2013). A similar contemporaneous tectonic setting existed along the north Indian margin as well (Kohn et al., 2010). The abundance of relatively young 1.9–1.7 Ga zircon grains in the Jhamarkotra Formation may result from syntectonic deposition along the active convergent margin, which is common along similar tectonic settings (e.g., Cawood et al., 2012). The introduction of younger $\sim 1.6$ Ga zircon grains into the Middle Aravalli group is consistent with a younger depositional age for this unit.
4.1.1. Late Paleoproterozoic phosphatic stromatolites in north India

The Jhamarkota Formation sample analyzed for detrital zircon grains was collected stratigraphically below the phosphatic carbonate in the Jhamarkota mine. The ~1.7 Ga maximum depositional age for this Jhamarkota Formation nullifies the interpretation that this unit was deposited during a ~2.0 Ga global phosphogenic event following the Great Oxidation Event (Papineau et al., 2009, 2013; Papineau, 2010). Phosphatic stromatolites are known in ca. 1.6 Ga late Paleoproterozoic rocks in both the upper Semri Group of the lower Vindhyan succession and the Gangolihat Dolomite of the Lesser Himalaya (e.g., Valdiya, 1969; Banerjee et al., 1986; McKenzie et al., 2011). The Himalayan–Vindhyan phosphatic deposits consist of branching columnar stromatolitic bioherms with columns exceeding 10 cm in diameter. The phosphatic horizons in those deposits are restricted to within only a few meters of the bioherm with the phosphate occurring in the inter-columnar spaces as phosphatic grainstone, as coatings on terrigenous material, and as crusts on the stromatolite columns, whereas the stromatolite build-ups themselves are mostly dolostone (Banerjee et al., 1986; Bengston et al., 2009; McKenzie et al., 2011). In both the Vindhyan and Himalayan deposits the phosphate does not occur throughout the stromatolitic lamination, and the phosphatic crusts around the individual columns appear to pinch-out along the stromatolitic heads in a discrete interval of the bioherms (e.g., McKenzie et al., 2011). These specific similarities may suggest a common mode of phosphogenesis in both regions.

The phosphate-bearing Jhamarkota stromatolitic bioherms are up to 10’s of meters in stratigraphic thickness (e.g., Banerjee, 1971) and are dominated by infrequently branching, elongate columnar stromatolites that are only a few centimeters in diameter (Fig. 5). In the Jhamarkota deposits the stromatolitic columns are phosphatic, with the intercolumnar space consisting primarily of massive dolostone. Therefore, there are some differences in mode of Carbonate–fluorapatite deposition between the Himalayan–Vindhyan and Jhamarkota phosphatic stromatolites, despite both being shallow water, stromatolitic phosphorites. The similar age among all of these phosphatic deposits suggests there may have been similar over-arching controls on carbonate fluorapatite precipitation across the north Indian margin during the late Paleoproterozoic. Whatever the cause, various stromatolitic bioherms created local environments that permitted phosphogenesis in northern India during this discrete interval of time. This is noteworthy given the general dearth of Precambrian phosphorites.

4.1.2. A mid-Proterozoic δ13C excursion?

The revised age determination for the Lower Aravalli Group also brings into question claims that δ13C enrichments in the Jhamarkota Formation are related to the ~2.1 Ga Lomagundi–Jatuli event. The Jhamarkota Formation has yielded variable δ13C values. Phosphatic horizons yield δ13C values around 0‰ whereas thick sections of massive dolostone yield variable δ13C values that range up to +11‰ (Sreenivas et al., 2001; Maheshwari et al., 2002, 2010; Purohit et al., 2010). Nitrogen and organic carbon isotopic values are similar for both phosphatic and non-phosphatic sections (Papineau et al., 2013). The dolostone with isotopically heavy carbon values is considered to sit stratigraphically below the phosphatic horizons (e.g., Sreenivas et al., 2001). Following the arguments of Papineau et al. (2013) for contemporaneous deposition of all...
Jhamarkotra strata, the $^{13}$C-rich Jhamarkotra deposits would have been deposited around $\sim 1.7$ Ga.

The positive values in the Jhamarkotra Formation are likely to record depositional $\delta^{13}$C signatures. Foremost, the carbonates are found in a relatively pure, organic-lean carbonate succession (rather than a carbonate-cemented siliciclastic unit) and most diageneric processes drive the $\delta^{13}$C values negative. The fact that the isotope excursion is found in a thick ($\geq 55$ m stratigraphic interval) unit with $\delta^{13}$C values exceeding $\pm 7\%$ (Maheshwari et al., 2002, 2010) also points toward a depositional, rather than diageneric, origin for the anomalous $\delta^{13}$C values: typical mechanic-zone $\delta^{13}$C enrichment in carbonate constitutes a relatively minor aspect of sedimentary successions (e.g., Irwin et al., 1977). Although the Jhamarkotra Formation has been metamorphosed to greenschist facies (Papineau et al., 2009, 2013), a metamorphic origin of the anomalously high positive carbonate $\delta^{13}$C values is highly unlikely. Therefore, all available evidence suggests that the Jhamarkotra Formation may host a previously unidentified late Paleoproterozoic positive $\delta^{13}$C excursion (Fig. 6).

The prevailing view is that the mid-Proterozoic ($1.8-0.8$ Ga) was characterized by carbonate isotope and general biogeochemical stasis (Brasier and Lindsay, 1998), which has given rise to the moniker the ‘boring billion’ (e.g., Holland, 2006). The potential implications of a billion years of carbon isotope stasis have been far reaching. For example, this framework has shaped models of eukaryotic diversification (e.g., Anbar and Knoll, 2002), and played a central role in models of environmental change and carbon isotope chemistry bracketing the Proterozoic (e.g., Swanson-Hysell et al., 2010; Bekker and Holland, 2012). If both the age and primary nature of this isotope excursion are corroborated, and if it in fact reflects global-scale marine processes, the presence of a significant late Paleoproterozoic positive carbon isotope excursion would dramatically affect views of the evolution of the carbon cycle during the Precambrian. Given the potential for the Jhamarkotra Formation to fundamentally reshape our view of biogeochemical cycling for a billion years of Earth’s history, additional work to rigorously test the validity of a ca. 1.7 Ga positive carbonate carbon isotope excursion is certainly warranted.

4.2. Revised ages of the Delhi Supergroup and miscorrelation of the North and South Delhi belts

A sample from the Alwar Group (RD4) of the southern Delhi Supergroup possesses a large population of 1.2–1.1 Ga detrital zircons ($\sim 1187$ Ma age peak) (Fig. 7). Therefore, the southern Delhi Supergroup cannot be 1.9–1.7 Ga as previously asserted. The $\sim 1.2$ Ga depositional age constraint together with reports of $987 \pm 6$
and 986 ± 2 Ma rhyolites associated with the uppermost part of the Delhi Supergroup (Deb et al., 2001) brackets the depositional ages of the southern Delhi Supergroup between ~1.2 and ~1.0 Ga. The age distribution from the southern sample differs from published age data from the Alwar Group of the North Delhi Belt (Kaur et al., 2011) as the northern sample contains a large population of ~1.7 Ga zircon grains with nothing younger (Fig. 7). A potential age discrepancy between the northern and southern Delhi groups has been previously recognized (Biju-Sekhar et al., 2003), although this discrepancy was attributed to differences in tectonic history of each “basin”. On the basis of data presented here, we suggest that the discrepancy results from a longstanding miscorrelation of strata between the two regions.

The age distribution from the ~1.7 Ga northern Alwar Group is similar to the Jhamarkotra Formation, which we have estimated to have a depositional age of ~1.7 Ga. Based on the similar depositional ages and detrital zircon age distributions, strata of the so-called North Delhi Belt likely represent the northern equivalents of the Aravalli Supergroup. Kaur et al. (2013) suggest syntectonic deposition for strata of the North Delhi Belt along an active continental arc system and based on data presented herein, we suggest a similar depositional environment for the Aravalli Supergroup. Deposition along a convergent margin contrasts the long-standing hypothesis that the Aravalli Supergroup was deposited along an active rift margin.

4.3. The Rajasthan Vindhyan successions and correlation across the north Indian margin

Forty-eight of the fifty zircon grains analyzed from the Semri Group sample (RVSI) yielded Pb/Pb ages between 2515 ± 4 and 2588 ± 41 Ma and the two other grains yielded ages of 1877 ± 7 and 1885 ± 17 Ma. This sample was acquired from coarse-grained feldspathic sandstone (Fig. 3a) and the abundance of ~2.5 Ga zircon grains likely reflects almost exclusive derivation of detritus from a proximal ~2.5 Ga felsic igneous source. The two ~1.8 Ga grains are close in age to the 1854 ± 7 Ma volcanic Hindoli rocks located ~150 km northeast of the Semri Group locality (Deb et al., 2002), as well as ~1.9–1.7 Ga plutons of the North Delhi Belt (e.g., Biju-Sekhar et al., 2003; Kaur et al., 2009, 2013), and the BGC-II of the southern ADOB (Buick et al., 2006). The Semri Group age distribution from Rajasthan is considerably different from a Semri Group age distribution from the Son Valley (Fig. 3) and direct correlation between these regions is not possible based on data presented here. Kaimur Group sandstone (RVK1) contains large populations of ~1.2 Ga (~1715 age peak) and ~1.6 Ga zircon grains. This is similar to both a published age distribution from the Son Valley Kaimur Group, which also produced a youngest age peak of ~1172 Ma, and age distributions from both the Rajasthan and Son Valley Bhandar groups (McKenzie et al., 2011) (Fig. 4). Together, these similarities support correlation of upper Vindhyan successions between the Rajasthan and Son Valley sectors.

While the abundance of grains from distinct age populations within each distribution is variable, the Kaimur Group distributions are strikingly similar to the age distribution of the southern Delhi Group. Most notable are the similar age peaks around ~1.2 and ~1.6 Ga in the Rajasthan Kaimur Group and Delhi Group, with both samples lacking ~2.5 Ga grains, which are common in all other age distributions (Fig. 4). Overall, strata of the ADOB have similar age-relationships to lower and upper Vindhyan successions, and it is suggested here that the Aravalli–Delhi supergroups represent the tectonically deformed equivalents of the Vindhyan successions, with the Aravalli–Delhi supergroups separated by the same ~500 million year unconformity present in the Vindhyan successions (Fig. 4). The similarity of detrital zircon age distributions in the Vindhyan successions and strata of the ADOB likely results from shared sediment sources, and thus these strata were deposited as part of a contiguous margin with Vindhyan strata deposited episodenpendent settings and the Aravalli deposited along the continental margin, rather than in discrete isolated basins as generally assumed.

5. Conclusions

We provide new age constraints on the sedimentary succession of the ADOB. The Aravalli Supergroup is constrained to be late Paleoproterozoic in age. The Jhamarkotra Formation has an estimated depositional age of ~1.7 Ga. Based on these revised ages, it is doubtful that the positive carbonate δ13C values measured in this unit are linked to the 2.2–2.0 Ga Lomagundi–Jatuli event. Therefore, this presents the intriguing possibility of an unrecognized late Paleoproterozoic positive δ13C excursion. If verified, this would call into question the idea of mid-Precambrian carbon isotope stasis, which has become a key facet of current models on the evolution of biogeochemical cycling in the Precambrian.

The Delhi Supergroup of the southern ADOB has a depositional age range of 1.2–1.0 Ga and is not correlative with the Delhi Supergroup of the North Delhi Belt. Strata of the northern belt are likely correlative with the Aravalli Supergroup. These late Paleoproterozoic strata were deposited syntectonically along an active convergent margin, rather than an active rift margin. Age relationships of the Aravalli–Delhi supergroups reflect those of the lower–upper Vindhyan successions and similar age distributions of detrital zircon grains from all regions are used to suggest that these strata were deposited across a contiguous margin, with Vindhyan strata representing episodenpendent deposits and strata of the ADOB representing the distal continental margin equivalents.

Acknowledgements

We thank Dr. N.K. Chauhan for local support in Udaipur, G. Gehrels, M. Pech, and N. Giesler for analytical assistance at the Arizona LaserChron Center, JS. Lackey for providing facilities and assistance for sample processing, and C. Lee for analytical assistance. Comments from M. Bickford, S. Long, J. Meert, H. Frimmel, and anonymous reviewers greatly improved the manuscript. This work was supported by National Science Foundation Grants EAR-1124303 to N. Hughes and EAR-1124518 to P. Myrow. McKenzie acknowledges the UT Austin Jackson Postdoctoral Fellowship.


