Chapter 4
Proterozoic Sedimentary Basins of India

Partha Pratim Chakraborty, S. K. Tandon, Sagnik Basu Roy, Subhojit Saha, and Pritam P. Paul

Abstract Indian Proterozoic geology includes a group of less disturbed and unmetamorphosed platformal sediment packages hosted within cratonic nucleii of Peninsular India and offers scope to study profound and irreversible changes in the atmosphere, hydrosphere and biosphere during the early history of the planet. Studies in these basin fills in the last two decades have resulted in significant advancements with respect to initiation and evolution of the basins in different tectonic settings, relationship with accretion and breakup of the supercontinents, paleoclimate and paleo-weathering patterns and ancient basin water chemistry. Acknowledging all these aspects, this contribution explored the possible connections of the basins with the 'supercontinent' cycles, viz. Columbia and Rodinia through this time period. From collation of geochronologic data, it is concluded that the most prevalent dates obtained from the basin fills fall in 1650–1450 Ma and 1100–1000 Ma. time bracket, concomitant with the breakup of supercontinent 'Columbia' and the amalgamation of the following assembly of supercontinent 'Rodinia'. A few may also be connected with the formation of 'Columbia', viz. Aravalli and Cuddapah, and the fragmentation of Rodinia, viz. Marwar.

Keywords Proterozoic · Sedimentary basins · Columbia · Rhodinia · Tectonics and sedimentation · India

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4.1 Introduction

A comparison of Precambrian and Phanerozoic–modern sedimentary records allowed workers to conclude that fundamental differences in sedimentation processes of the two systems lie in rates and intensities of weathering, erosion, lithification, diagenesis etc. (Eriksson et al. 2001; Bose et al. 2012) and not as much in fundamental controls behind basin formation and their filling, viz. tectonics, magmatism, eustacy or climate (Donaldson et al. 2002). Therefore, it is logical to question why and to what extent Precambrian sedimentary basins and their fills differ from those of the later Phanerozoic era. Pondering on this question, several works (Eriksson et al. 1998; Bose et al. 2012) highlighted some noticeable differences in Precambrian sedimentation patterns, viz. lack of vegetation and limited development of soil, lack of bioturbation, greater light penetration in ocean water in the absence of plankton and prolific growth of microbial mats in shallow-marine, terrestrial and aquatic realms, and suggested a uniqueness in Precambrian sedimentation history that warrants special investigation. Besides, sedimentary basins belonging to this time have also drawn attention because of several unique and irreversible changes which include shift in marine redox conditions, evolution and diversification of eukaryotes, appearance of metazoan life and dramatic reorganisation of surface ocean, benthic ecosystems and environments (Reddy and Evans 2009).

Indian Precambrian geology is bestowed with several Proterozoic sedimentary basins (Mazumder and Eriksson 2015) that offer the opportunity to study and understand many such details of Precambrian surface processes. Since Holland (1913) introduced the term *Purana basin*, undeformed and unmetamorphosed 'Proterozoic' platformal sediment packages (Fig. 4.1) spread over different parts of Peninsular India became the focus for sedimentologists to study the uniqueness of Precambrian near surface processes. Collectively, these unfossiliferous basin fills constitute 22% exposure area of the Precambrian rocks of India and have unconformable relationship with basement, constituted of Archean to Paleoproterozoic basement gneisses, granites and schistbelts (the 'Eparchean Unconformity'). Chakraborty et al. (2010), Basu and Bickford (2015) and Meert and Pandit (2015) have attempted the collation of data on lithostratigraphy and structural disposition of these basins with the aim of understanding (1) the correlation between basin fills and (2) the classification of the basins in time domain. These reviews not only highlighted the inadequacy of robust geochronologic data and process–product modelling for basin fill packages but also strongly commented upon the necessity of reclassification of these basins in terms of geotectonic setting taking into consideration tectonic events and opening/closing timings of the basins. Additionally, the occurrence of exquisitely preserved microbial mat-induced sedimentary structures (MISS) and redox-sensitive chemical sediments, viz. iron formation, pyrite, phosphate, barite etc., in many of these basin fills prompted workers to engage in the ongoing debate pertaining to atmospheric and hydrospheric chemical evolution through the Precambrian; while several workers claim a single-step change from an original reducing atmosphere/hydrosphere to anoxidising one, many others differ and support a multistep changeover through the

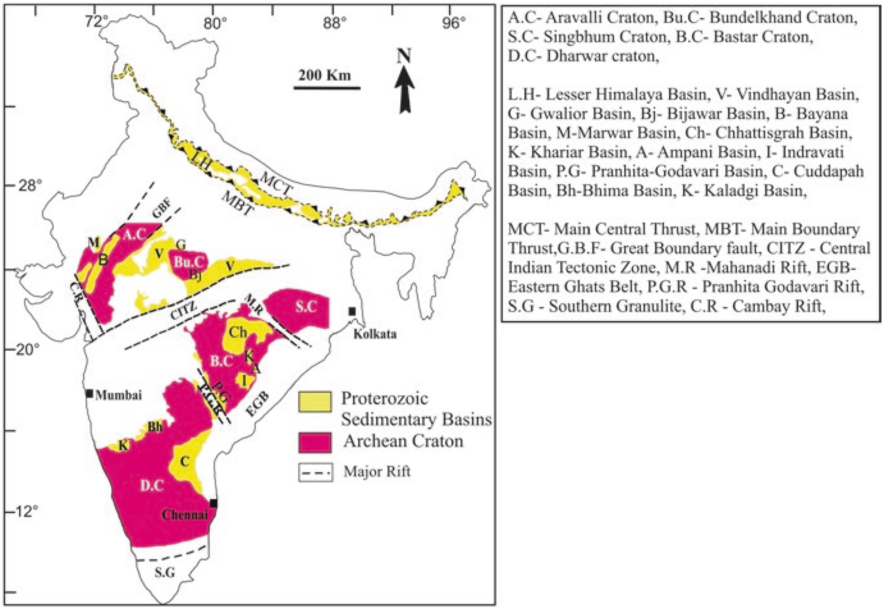

Fig. 4.1 Proterozoic cratonic basins in Peninsular India and host cratons. Also shown is distribution of Lesser Himalaya sediments

Proterozoic, i.e. anoxic–suboxic–oxic–sulphidic–oxic (Ohmoto 2004). The present review aims at a holistic understanding including basin opening/closing in the backdrop of supercontinent history, i.e. with the breakup/amalgamation of supercontinents, viz. Columbia and Rodinia, basin filling motif in spatiotemporal framework, crucial role of microbial mats on siliciclastic sedimentation and clues obtained so far regarding the oxygenation history of atmosphere/hydrosphere in the early history of the Earth.

Beside the Purana basins, Precambrian sedimentary records in India also include (1) deformed, meta-sedimentary successions hosted in greenstone belts (Bababudan, Chitradurga etc.), fold belts (Aravalli-Delhi Fold Belt) and mobile belts (CITZ, Eastern Ghats) and (2) Paleoproterozoic to early Phanerozoic Lesser Himalayan succession as part of Cenozoic Himalayan orogen, bounded between Main Boundary Thrust (MBT) in the south and Main Central Thrust (MCT) in the north, respectively. In this chapter, we confine our discussion to undeformed intra-/epi-cratonic successions floored by continental crust, i.e. hosted within the cratonic nuclei of Indian Peninsula, and their counterparts present within the Himalayan orogen, i.e. the Lesser Himalayan succession. Going beyond the shallow-marine, epeiric setting panacea, the present contribution attempts highlighting the recent understanding/debate on tectonic settings of basins since synchronicity of opening and closing of many basins can be assessed based on recent geochronological data. By the terms ‘opening’ and ‘closing’ of a basin, here we refer to the time when a basin started and stopped receiving sediment. We classify basins based on their host cratonic nuclei, viz. Aravalli-Bundelkhand, Bastar and Dharwar.

4.2 Aravalli-Bundelkhand Craton

Hosted within and fringing the craton, there are a number of basins (Fig. 4.2), those ranging in age Paleoproterozoic to Paleozoic. Among these, some basin successions, viz. Aravalli and Delhi Supergroup of rocks, are represented by deformed metasediments and others by deformed/undeformed but unmetamorphosed sediment packages. Sedimentation in the Aravalli ocean basin is dated between 2.4 Ga and 1.8 Ga and correlated with the formation and breakup of the supercontinent 'Columbia' (Meert and Pandit 2015). Meert and Pandit (2015) agree with opening of the Delhi basin between 1.7 Ga and 1.0 Ga with breakup of the 'Columbia' supercontinent. The unmetamorphosed sediment packages include (1) basins of North Delhi Fold Belt, viz. Lalsot-Bayana, (2) basin in the western part of Aravallis (i.e.

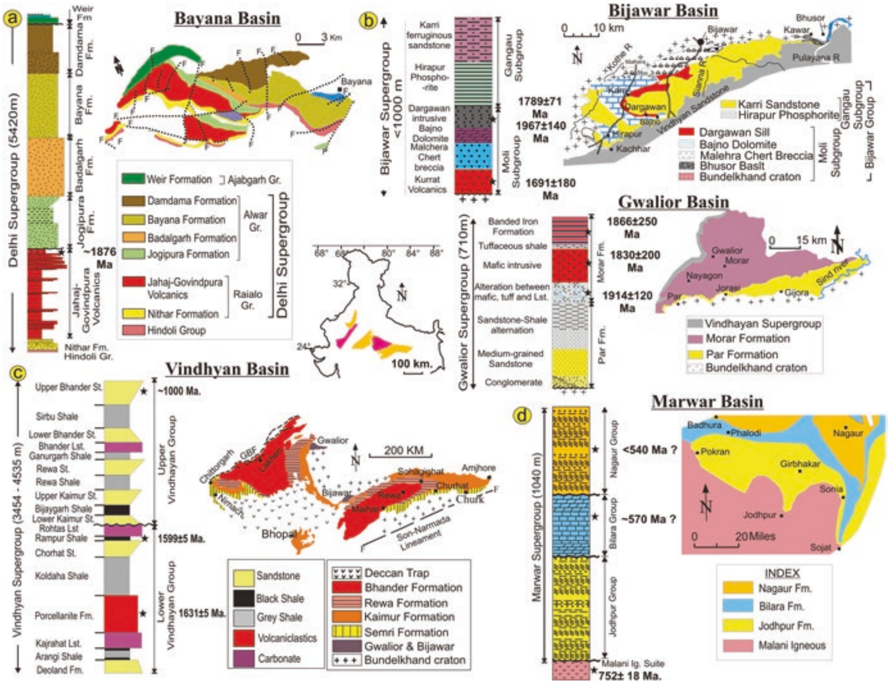

Fig. 4.2 Basins, viz. Bayana, Bijawar, Gwalior, Vindhyan and Marwar, hosted within or fringed around the Aravalli-Bundelkhand craton. General stratigraphy of basins, estimated total sediment thickness and geochronology data obtained from different stratigraphic levels of basin successions are shown alongside

Marwar basin) and (3) basins fringing the western and southern margin of the Budelkhand craton, i.e. Gwalior, Bijawar, Vindhyan etc.

4.2.1 Bayana Basin

The undeformed and nearly unmetamorphosed volcano-sedimentary sequence in 1.8 Ga old NE–SW trending Bayana basin at the easternmost fringe of the North Delhi Fold Belt (Fig. 4.2a) records tectonically guided sedimentation in an intracratonic-rift setting (Raza et al. 2012). Recurrence of conglomerate (with intra- and extra-basinal clasts)-sandstone packages all through the basin fill, rapid alteration of facies types representing paleoenvironmental shift between continental fluvial and shallow-marine tidal/deltaic setting and dominant continental block with minor recycled orogen provenance for clastic detritus in the basin in Dickinson Qm-F-Lt plot (Raza et al. 2012) bear telltale signatures for tectonically controlled sedimentation under the influence of multiple palaeoslopes. From paleocurrent analysis, Singh (1988) inferred the 'Dausa uplift' as the principal provenance for the basin, while from sediment geochemical data, Raza et al. (2012) suggested the Mesoarchean gneisses and Late Archean granites of Bundelkhand gneissic complex as the provenance. Continued extension across the basin axis resulted in outpouring of basic to acid volcanics.

4.2.2 Basins Fringing the Bundelkhand Craton

4.2.2.1 Gwalior and Bijawar Basins

Encircling the Bundelkhand craton, a string of Paleoproterozoic basins, viz. Bijawar and Gwalior, records the pre-Vindhyan sedimentation history in the north Indian craton (Fig. 4.2b). Available geochronological data from interbedded basic sill units belonging to both 'Bijawar' and 'Gwalior' successions have yielded comparable dates, thereby suggesting their contemporaneity. The emplacement ages of two phases of dykes within the basement of Gwalior basin, i.e. within the Bundelkhand Granite Massif, are 2150 Ma and 2000 Ma, respectively (40Ar/39Ar systematics; Mallikharjuna Rao et al. 2005). Rb–Sr dating of mafic rocks present within the basin succession has yielded dates of 1830±200 Ma (Rb–Sr isochron; Ramakrishnan and Vaidyanadhan 2010) and 1854±7 Ma (U–Pb zircon Concordia; Deb et al. 2002), respectively. Taking the dates into consideration, Absar et al. (2009) bracketed the Gwalior depositional history between 2000 and 1791 Ma. From the Bijawar basin, the Dargawan sill and the Kurat lava are dated as 1789±21 and 1691±180 Ma, respectively, using Rb–Sr systematics (Haldar and Ghosh 2000).

Despite being coeval, analogous rift-related origin and sediment supply from a common provenance, i.e. the BGGC, the Gwalior and Bijawar basins vary in their sedimentation patterns. While clastic sedimentation ranging between continental (alluvial fan and braided fluvial) and proximal shelf setting mark early sedimentation in the Gwalior basin (Paul 2017), the Bijawar basin records early chemical sedimentation expressed as Bajno Dolomite and Malhera Chert Breccia Formations with a very early, restricted record of volcanoclastic sedimentation in the form of the Kawar Formation. Sedimentation patterns differ in the later parts of depositional histories of the two basins as well. The Gwalior basin records BIF of ca. 1.85 Ga time period as Morar Formation, whereas the Bijawar basin records phosphorite deposition (Chakraborty et al. 2015a; Absar et al. 2009). Although both of the basins record syn-depositional volcanic/volcaniclastic event(s) in the form of occurrence of basaltic/basalt–andesite sills, the occurrence of iron formation in the later part of Gwalior sedimentation history and its absence in the Bijawar succession are interpreted as a reflection of variable oxidation conditions in the water columns of the two basins. Chakraborty et al. (2015a, b) observed dominant magnetite mineralogy in iron phase of the argillaceous Morar sediments of the Gwalior basin except for the shallow peritidal part of the basin where algal growth created some oases of oxygenation and allowed hematite precipitation in association with carbonate and chert. From the presence of carbonate and chert veins transgressing magnetite bands, these authors inferred hematite–magnetite transformation at the diagenetic stage.

4.2.2.2 The Vindhyan Basin

Overlying the Gwalior and Bijawar basins with unconformity, the Vindhyan basin, the largest among all the ‘Purana basins’ and the second largest among all the Proterozoic basins of the world, encircles BGC to the south and west in the form of a broad syncline (Fig. 4.2c). Since the Aravalli, Delhi and Satpura orogenic belts border it, some workers considered the basin as a peripheral foreland basin related to the southerly dipping subduction prior to the collision of Bhandara and Bundelkhand cratons (Raza and Casshyap 1996). Chakraborti et al. (2007) supported the idea from Nd isotope study. Other views include an intracratonic rift origin (Ram et al. 1996). Bose et al. (2001) correlated the sedimentary and geophysical attributes to an intracratonic rift to sag transition. Among these, a broad consensus that prevails in literature is a westward opening epicontinental basin model (Bose et al. 2001).

Attempts were made to correlate Vindhyan successions present in various sectors, viz. Son valley, Rajasthan or Bundelkhand using isotope stratigraphy (Ray et al. 2002). Kumar (2001) dated sedimentary glauconites from sandstones of the Semri Group near Chitrakut area by Rb–Sr method and set a strict limit at 1650 Ma for the onset of Vindhyan sedimentation. More robust ages came from U–Pb zircon dates (1631.2±5.4 Ma and 1630.7±0.8 Ma) obtained from the Porcellanite Formation of the Semri Group, Lower Vindhyan, by Ray et al. (2002). Rasmussen et al. (2002) also dated zircons from the same formation exposed near Churhat area and reported its age as 1628±8 Ma. Subsequent dating by various authors resulted in more or less similar ages, and finally initiation of sedimentation in the Vindhyan basin is constrained at >1631± 0.8 Ma. A tuffaceous bed present within the Rampur shale of Lower Vindhyan exposed near Rampur Naikin area was dated by Rasmussen et al. (2002) to 1599±8 Ma age, thereby constraining the age of lower Vindhyans broadly between >1631 Ma and <1599 Ma. Sarangi et al. (2004) reported Pb–Pb isochron age of 1599±48 Ma from the limestone of Rohtasgarh Formation and suggested cessation of Lower Vindhyan sedimentation in a time frame <1599±48 Ma.

The age dating of upper Vindhyan remained more elusive due to nonavailability of dateable material. The Pb–Pb isochron of 650 Ma (Ray et al. 2003) from the Bhander Limestone in uppermost Vindhyan is debated and discarded because of large analytical error, i.e. 770 Ma. Also, the age of Bhander limestone is not older than 750 Ma, as argued by Ray et al. (2003), from a comparison of its Sr isotope values with Sr isotope secular variation through the Precambrian time. De (2003, 2006), on the basis of purported Ediacara-like fossils, proposed an age less than 635 Ma for the Bhander Limestone. A more recent study by Malone et al. (2008) with the use of paleomagnetism in 1070 Ma old Majhgawan kimberlite intrusion within the Kaimur Formation and U–Pb detrital zircon geochronology from the Upper Bhander sandstone allowed an inference of 1000 Ma age for closing of the basin. Although detrital zircon age refers to the age of provenance, the absence of any younger grain despite occurrence of younger provinces around the basin gave strength to the argument of closing age of the basin by Malone et al. (2008). Subsequently, Gopalan et al. (2013) carried out Pb–Pb geochronology from three carbonate horizons of Upper Vindhyan succession, viz. Bhander, Balwan and Lakheri, and obtained ages of 908±72 Ma, 886±180 Ma and 1073±210 Ma, respectively. Despite having large error margins, these authors suggested an age of 900 Ma for the carbonate units. Considering these dates, a broad age bracket could be drawn for Vindhyan sedimentation history between >1631 Ma and 900 Ma, spanning over 600 Ma between the late Paleoproterozoic and the end of Mesoproterozoic.

The basin represents one of the world's best exposed Precambrian analogues for platform-type shallow-marine to nonmarine depositional setting (Bose et al. 2001). The paleogeographic setting was initially identified as near-shore marginal marine, belonging to barrier bar lagoon, chenier, tidal flat and beach with intermittent subaerial exposure. Later, workers documented sedimentary facies belonging to shelf (often storm infested), continental fluvial and aeolian setting (Bose et al. 1999). The only divergent view was that of Bhattacharyya (1996) who suggested that the Vindhyan sedimentation took place entirely in terrestrial environment such as lacustrine, fluvial and aeolian and refuted his own earlier emphasis on marginal marine sedimentation. This view, however, did not receive support from subsequent workers. Depositional paleoslope was estimated to be gentle throughout the basinal history. Paleocurrent direction had consistently been northwestward implying terrigenous supply from a south/southeastern source; dominance of fine-grained and texturally mature siliciclastics as well as carbonates points to low relief in the source (Bose et al. 2001). Analysing framework grain composition and geochemistry (major, trace and REE) of Bhander sandstones from Maihar to Nagod area, geoscientists suggested a possible continental interior to recycled orogen provenance for the clastics. Paleoclimate had probably been warm and humid to facilitate large-scale elimination of the labile minerals (Bose et al. 2001).

Since categorisation of the basin as 'Frontier basin' by Director General of Hydrocarbon (DGH), Govt. of India for hydrocarbon prospect, attempts were made to evaluate source rock potential of its argillaceous intervals. Indeed, total organic carbon (TOC) analysis of Vindhyan shales reveal Arangi Shale (3.673–8.434%; n = 07), Rampur Shale (0.9278–3.624%; n = 10) and Bijoygarh Shale (2.815–3.356%; n = 07) with good to very good values, i.e. more than 1.5%. In addition, C-H-S analysis and Rock-Eval pyrolysis of organic matters indicate their Type III (humic) affinity with high carbon (C) and very low to negligible hydrogen (H) contents and, hence, gas-prone character. Most Shale Formations reveal under- or over-matured signature, except for the Arangi and Bijoygarh Shale Formations, which yield high TOC values and 'mature' organic matters (Dayal et al. 2014; Singh 2015).

Organosedimentary structures (stromatolites) are well documented from different carbonate formations of the Vindhyan Supergroup (Sharma 2006), and the discovery of putative Metazoan traces by Seilacher et al. (1998) drew attention of the geologic community worldwide. Integrated paleontologic–geochronologic investigation by Bengtson et al. (2009) confirmed the presence of fossils, viz. annulated tubes, coccoidal microbial fabrics similar to *Grivanella* and *Renalcis* etc. within late Paleoproterozoic rocks of the basin, which otherwise resemble forms found in rocks of Cambrian age. Working on the 1.6 Ga Tirohan Dolomite of Lower Vindhyan, Bengtson et al. (2017) reported crown-group multicellular rhodophytes, viz. *Rafatazmia* and *Ramathallus*, and suggested 400 Ma dating back of red algae fossil record.

4.2.2.3 Marwar Basin

The Late Neoproterozoic–early Cambrian sediments of the basin, covering a vast area on the Rajasthan shelf, represent the westerly dipping eastern flank of the Indus shelf of the Indo- Arabian geological province (Fig. 4.2d). Cozzi et al. (2008), on the basis of litho- and chemostratigraphy, correlated Huqf Supergroup, Oman with Khewra, Kussak and Jutana Formations of Salt Range and Marwar Supergroup of Western Rajasthan. Overlying ~700 Ma (681 Ma to 771 Ma; Torsvik et al. 2001; Gregory et al. 2009) old Malani Igneous Suite (MIS) of rocks, sedimentary succession of the Marwar Supergroup is subdivided into lowermost Jodhpur Group, middle Bilara Group and uppermost Nagaur Group. From putative traces of trilobite in the upper part of the Nagaur Group, Kumar and Pandey (2008) attributed a Paleozoic time frame for the Nagaur rocks. McKenzie et al. (2011) estimated La-ICPMS detrital zircon maximum age of ~540 Ma from sandstones of the Nagaur Formation. In the absence of fossil evidence, Ansari et al. (2018) relied on $^{87}Sr/^{86}Sr$ and Ca/Sr values to infer probable age of Gotan limestone of Bilara Group as 520–530 Ma and 570 Ma, respectively. A serious question is posed with these new dates on validity of the assumption that the Marwar Supergroup is a continuation of the Vindhyan Supergroup across the Aravalli axis.

For Pokhran, boulder bed opinions vary between its glacial origin (Chauhan et al. 2004) and alluvial/fluvial origin (Meert and Pandit 2015). From process-based sedimentology, Sarkar et al. (2012) interpreted the Sonia Formation of Jodhpur Group to be a product of sea-level low stand, constituted of a shallow-marine interval bounded between braided fluvial deposits both below and above the formation. In an earlier study, Sarkar et al. (2008) documented an exquisite array of microbially mediated sedimentary structures (MISS) from the shallow-marine interval. Except these works, no process-based sedimentology is available for the rest of the Marwar Supergroup. However, expecting the possible presence of Precambrian–Cambrian transition, a number of stable isotope studies ($\delta^{13}C$, in particular) were carried out from the Bilara Formation. Observing a negative shift in carbon isotope value (–4.3‰) in the lower part of Bilara succession and a gradual positive shift in its upper part, Pandit et al. (2001) suggested a possible presence of Neoproterozoic–early Cambrian transition. The idea was also supported by Mazumdar and Bhattacharya (2004) with negative carbon isotope values from the lower part of Bilara succession. From strontium (Sr) isotope composition and enriched sulphur isotope values of Bilara carbonate-hosted sulphate (avg. 33.8±3.1) and Hanseran evaporite (avg. 32.4± 3), Mazumdar and Strauss (2006) correlated Bilara signatures with late Neoproterozoic global analogues between 600 and 500 Ma. However, Ansari et al. (2018) have argued in favour of Ediacaran 'Shuram' excursion from the Bilara succession with the help of strong negative excursion (-8‰to -10‰) in $\delta^{13}C$ values, similar to the values recorded from Yangtze Gorges platform, China, and explained it as a result of organic matter oxidation and burial at sea bottom for a long time triggered by convergence of surface oxygenated water in deep sea. Recently, Chakraborty et al. (2019) documented meters-thick layers of soft sediment deformation (SSD) structures present at different stratigraphic levels within the Bilara limestone and suggested correlation with SSD structures reported from the time-correlative stratigraphic successions present in erstwhile adjoining tectonic terrains, e.g. China, Siberia etc., at the time of Precambrian–Cambrian transition.

4.3 Bhandara (Bastar) Craton

Delimited by two regional-scale crustal discontinuities (viz. Pranhita–Godavari rift on south–southwest and Mahanadi rift on north–northeast) and the NNE–SSW trending mobile belt (viz. Eastern Ghats Mobile Belt (EGMB) on east–southeast), the Bastar craton of central India hosts a number of Meso- to Neoproterozoic basins of widely varying spatiotemporal framework (Fig. 4.3). These include Chhattisgarh and adjoining basins, viz. Khariar, Ampani, Sabari (Sukma) and Indravati.

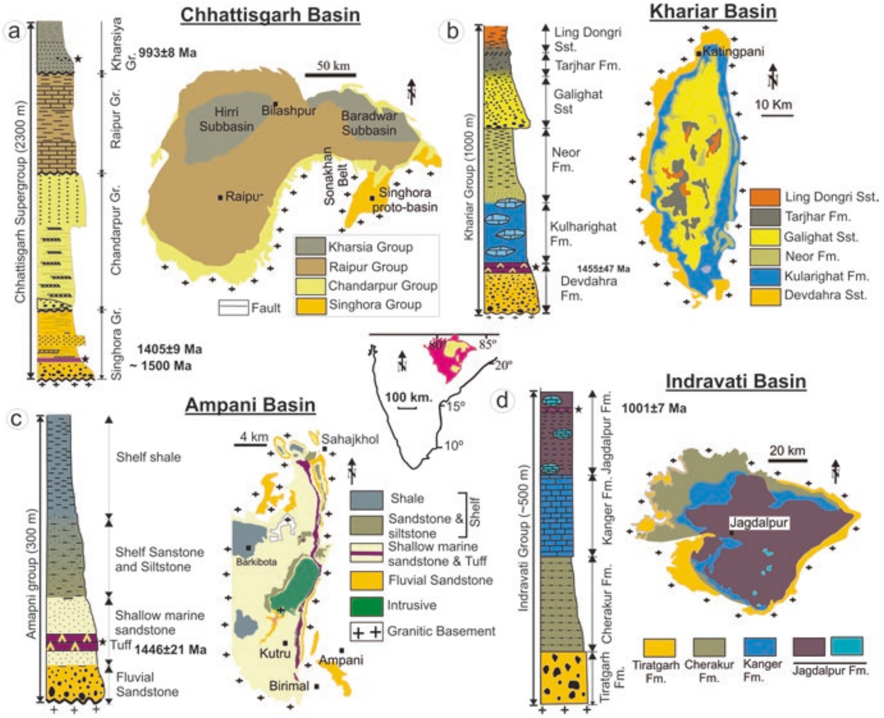

Fig. 4.3 Basins within or at the margin of Dharwar craton, viz. Cuddapah, Pranhita–Godavari, Kaladgi-Badami and Bhima. Basin stratigraphy, estimated lithopackage thickness and geochronology data generated from different stratigraphic levels of basin successions are shown alongside

4.3.1 Chhattisgarh Basin

Being the third largest Proterozoic basin in India, the Chhattisgarh basin covers an aerial extent of 33,000 km^2 and hosts a c. 2300 m-thick mixed siliciclastic–carbonate–phosphorite/evaporite succession (Fig. 4.3a). A cluster of Archaean/Paleoproterozoic rocks form the basement for the basin which includes unclassified Archaean gneisses of tonalite–trondhjemite–granodiorite (TTG) affinity in the east and extreme SE, meta-sedimentary rocks and metavolcanics of NW–SE-trending Sonakhan greenstone belt in the west and correlatives of Dongargarh granitoids in the south. Aeromagnetic imaging identified the basin as a low-anomaly zone (–30 to +60 nT) in contrast to its high-anomaly granite/gneiss basement (–100 to +128 nT). A difference of 0.8 km in thickness estimation of Chhattisgarh lithopackage can be noticed between the gravity survey conducted in the northeastern part of the basin (3.5 km; Singh et al. 2006) and measured lithostratigraphic thickness (2.7 km; Das et al. 1992). It is, however, difficult to assess whether the observed difference is because of errors involved in different measurement methods or it is a reflection of pre-sedimentation basement topography (Chakraborty et al. 2015a, b). None of the available geophysical models have reported any pervasive basin-scale structural grain, namely, fault, lineament and so on, within the basement of the basin.

In the last two decades, a number of studies have contributed in understanding depositional processes vis-a-vis basin filling motif in spatiotemporal framework; geochronology of concordant and discordant lithodemic units with employment of robust isotopic systematics; documentation of structural grains, wherever present; limited but significant subsurface geophysics in transects; and geochemistry of chemical sediments, including stable isotopic signatures. Revising the existing three-tier stratigraphy of the basin offered by Das et al. (1992), viz. Singhora Group, Chandarpur Group and Raipur Group, recent studies (Patranabis-Deb and Chaudhuri 2008; Chakraborty et al. 2015b) have proposed a four-tier stratigraphy with the addition of new Group above the Raipur Group, i.e. the Kharsiya Group.

The availability of concordant tuffaceous strata at different stratigraphic levels within the Chhattisgarh lithopackage allowed workers to apply a well-constrained chronology with robust geochronological systematics (U–Pb zircon SHRIMP, Sm–Nd monazite) in terms of both initiation and closing age for the basin. These studies have established the Mesoproterozoic time frame of the basin on a strong basis. The perception change started with the work of Patranabis-Deb et al. (2007), who reported 990–1020 Ma age zircon grains from a tuffaceous layer present in the upper part of the Chhattisgarh succession, exposed near the Sukhda area. Since then, other studies (Das et al. 2009; Bickford et al. 2011a, b) involving zircon and monazite grains retrieved from tuff/volcaniclastic layers in its basal part that is, the Singhora tuff (c. 1500 Ma Sm–Nd monazite electron probe microanalysis (EPMA), Das et al. 2009; 1405±9 Ma, Bickford et al. 2011a) present at the contact between the Rehatikhol and Saraipali Formation of the Singhora Group, and the uppermost part, that is, the Dhamda tuff (correlatable with the Sukhda tuff; 993±8 Ma U–Pb SHRIMP zircon, Bickford et al. 2011a, b) sandwiched within the Tarenga Formation have assigned the Chhattisgarh lithopackage to a well-constrained Mesoproterozoic time frame.

Products of continental (alluvial fan; Patranabis-Deb and Chaudhuri 2007; Chakraborty et al. 2009; and braid plain, Chakraborty and Paul 2005), transitional (shoreface, foreshore and beach, tidal estuary and delta; Patranabis-Patranabis-Deb and Chaudhuri 2002; Chakraborty and Paul 2008), shallow-marine (storm-dominated, intertidal and subtidal, occasionally lagoonal; Das et al. 1992; Patranabis-Deb and Chaudhuri 2002) and distal marine below wave base (Chakraborty and Paul 2008) are documented from different stratigraphic levels of Chhattisgarh succession, in particular, from the siliciclastic intervals. Moitra (1995) estimated a pH value above 8.2 and a temperature between 40 and 50 °C in the Charmuria Sea with shifting anoxic and oxygenic conditions. Sarkar et al. (2010) recorded δ^{34}S values of 26.3±0.9‰; ($n = 12$) from pyrite grains of Charmuria limestone and interpreted them as a corroborative signal for Proterozoic sulphidic deep anoxic ocean. From the occurrence of barite, glauconite and iron oxide in the Gunderdehi shale, Moitra (1995) suggested an oxidising shallow oceanic condition. From Chandi limestone, Chakraborty et al. (2002) reported enriched δ^{13}C values (2.27–3.89; mean 3.19±0.6‰; $n = 14$) and interpreted it as a sign of higher organic productivity. Extensive stromatolite growth in the Chandi (Raipur) limestone Formation supports the contention. The view is also supported in a recent work by George et al. (2019) where increased organic carbon burial in course of deposition of Charmuria and Chandi limestone is suggested from elevated $\delta^{13}C$ signature (2.6–3.6‰). Although no basin-scale study is available for the Raipur (Chandi) limestone to decipher the carbonate platform geometry, on the basis of limited facies and stable isotope signature, Chakraborty et al. (2002) suggested paleogeographic variation in Raipur carbonate ramp between inner (above fair weather wave base) and outer ramp (below storm wave base). Unlike intracratonic platforms, availability of higher accommodation in Raipur carbonate ramp was visualised by these workers based on the presence of thick autoclastic conglomerate units.

4.3.2 Khariar, Ampani and Indravati Basins

Aerially separated from the Chhattisgarh basin by gneissic basement, successions representing the Khariar, Ampani and Indravati basin fills (Fig. 4.3b–d) occur as outliers within the Bastar craton and lithostratigraphically correlated with Chhattisgarh succession. Working on the northern part of the Khariar basin, Datta (1998) subdivided the Khariar succession into three informal units, viz. the lower sandstone, middle shale and upper sandstone, and correlated the succession with the Chandarpur Group of rocks of Chhattisgarh Supergroup. Das et al. (2001) assigned a formal lithostratigraphic status for the succession and termed it as 'Pairi' Group and further subdivided it into six constituent formations. Recently, Das et al. (2009) obtained 1455±47 Ma age through U–Th–total Pb EPMA geochronology of monazite and zircon grains from porcellanitic tuffaceous units sandwiched between the lower coarse arenaceous strata and middle argillaceous strata. From geochronological database, these workers suggested correlatibility of the Khariar succession with the lowermost part of the Chhattisgarh Supergroup, i.e. the Singhora Group, instead of the middle tier, i.e. the Chandarpur Group, as suggested by Datta (1998).

In a recent study involving mapping, deconvolution of deformation pattern and process-based facies analysis, Chakraborty et al. (2017) deciphered products varying between continental fluvial and distal marine from the Ampani lithopackage. From U–Th–total Pb electron probe microanalysis of monazite grains retrieved from a tuffaceous unit present within the Ampani lithopackage, Das et al. 2015 deciphered an age of 1446±21 Ma as age of crystallisation and proposed (1) correlation of the Ampani and Khariar (1455±47 Ma) successions with basal-most Group of the Chhattisgarh succession, i.e. the Singhora (c. 1500 Ma) Group, not with the middle Group, i.e. the Chandarpur Group, as suggested in Ramakrishnan and Vaidyanadhan (2010) and (2) incidence of a major felsic volcanic event during c. 1450 Ma at the eastern margin of the Indian craton.

Except for subdividing the basin succession in four tiers, i.e. Tiratgarh, Cherakur, Kanger and Jagdalpur Formation, in order of superposition and broad description of lithology, no process-based facies and paleoenvironmental study is available for the

Indravati basin succession. Recently, Mukherjee et al. (2012) carried out U–Pb isotopic analyses (LA MC-ICPMS) of magmatic zircons separated from the Birsaguda tuff belonging to the Jagdalpur Formation and suggested closure of sedimentation history of the basin at around 1001±7 Ma, analogous to the closing histories of the Vindhyan and Chhattisgarh basins. In addition, the recent geochronological data has raised a strong doubt on the validity of LA-ICPMS U–Pb age (620±30 Ma) from autometasomatic titanite given by Lehmann et al. (2007) from the Tokapal and Bhejripadar kimberlite pyroclastics, hosted within the Kanger Formation, present below the Jagdalpur Formation.

4.4 Dharwar Craton

Being the largest cratonic block in the southern half of the Indian peninsula, the Dharwar craton is subdivided into two distinct elements demarcated by the Closepet granite (2.7–2.5 Ga) in between the Western Dharwar (WDC), comprised of older greenstone belts (Sargur, Bababudan, Chitradurga), and the Eastern Dharwar (EDC), constituted of younger greenstone remnants (Sandur, Ramgiri, Kolar-Kadiri; Jayananda et al. 2012).

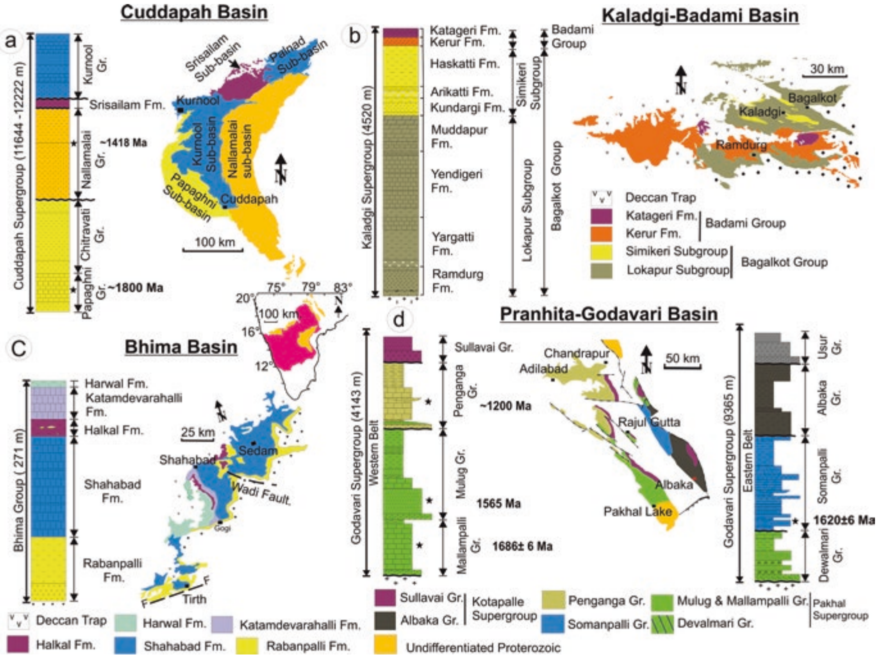

Fig. 4.4 Basins, viz. Chhattisgarh, Khariar, Ampani and Indravati, hosted with the Bhandara (Bastar) craton. Basin stratigraphy, estimated lithopackage thickness and geochronology data generated from different stratigraphic levels of basin successions are shown alongside

4.4.1 Cuddapah Basin

Hosted within the EDC, the crescent-shaped Cuddapah basin (Fig. 4.4a), ranging in age from Paleoproterozoic to Neoproterozoic, occupies an area of about 44,500 km^2 and hosts an ~12 km thick package of sediments and volcanics distributed in four subbasins, viz. Papaghni, Kurnool, Srisailam and Palnad (Saha and Patranabis-Deb 2014). From a range of geophysical investigations (Gupta et al. 2003), the following have been deduced: (a) a 10–11 km thick sedimentary pile over a 40 km thick crust in the eastern part of the basin, (b) step faults in the basement, (c) a mafic–ultramafic lopolith at a shallow depth under the south western part of the basin where mafic sills and volcanics are exposed and (d) an easterly dipping thrust fault at the eastern margin where high-density lower crust of the EGMB is upthrusted (Chakraborty et al. 2009). The Cuddapah sediments in the western part (Papaghni and Srisailam subbasins) are unmetamorphosed and almost undeformed, whereas in the eastern part, the Nallamalai Fold Belt shows considerable deformation in the form of a fold–thrust belt (Saha and Chakraborty 2003).

Traditionally, the Cuddapah succession is divided into (1) the Cuddapah Supergroup and (2) the Kurnool Group. Recent studies (Saha and Patranabis-Deb 2014), however, subdivided the succession into four unconformity-bound 'Sequences' and assigned those to syn- and post-rift history of the basin; while 'Sequences' dominated by conglomerate, feldspathic immature sandstones are tied up with syn-rift phase, the post-rift 'Sequences' are comprised of quartz arenites and carbonates. From lithological and petrological consideration, the Cuddapah sediments are identified as products of alluvial fan, fan delta, delta (both tide and storm influenced), complex beach, barrier-spit complex, subtidal to intertidal, offshore and carbonate shelf environments. The basin depocenter shifted with time, which is evident from the deposition of the Cuddapah Supergroup in different subbasins (viz. Papaghni, Nallamalai and Srisailam) and that of the Kurnool Group within the Kurnool and Palnad subbasins.

Isotopic age data suggest initiation of volcanic activity, and extension in the basin started at least 1900 Ma ago. Bhaskar Rao et al. (1994) dated doleritic intrusions from the Vempalle limestone to 1800 Ma. The Chelima lamproite intrusion within the Cumbum Formation, dated at 1418 Ma (Rao et al. 1999a), constrains the age limit for the Cuddapah Supergroup. No robust geochronological age is available from the Kurnool basin. U–Pb (SHRIMP and LA- MC-ICP MS) age determination from zircon grains of a suggested ash bed present within the Owk Shale (Saha and Tripathy 2012) is refuted by Bickford et al. (2013) on the basis of discounting volcanic origin of the bed and detrital character of zircon grains. Hence, the age of Kurnool Group, in general, and of the Owk Shale, in particular, remains elusive till date.

Opinions vary on the tectonic model and the mechanism of accommodating sediments of huge thickness (>12 km) within the basin. Taking into consideration sedimentation pattern, facies stacking and 'Sequence' development motif, Saha and Patranabis-Deb (2014) suggested evolution of the basin in a riftogenic setting.

These workers suggested initiation of each ‘Sequence (Cycle)’ in a rifting mode followed by stable subsidence when the basin evolved in the form of a large epicontinental sea. Alternatively, a peripheral foreland origin is proposed by Singh and Mishra (2002) whereby eastward subduction of the Dharwar craton is invoked for the collision and resultant deformation within the Nallamalai Fold Belt. Other groups of workers, however, proposed repeated heating and thermal upwarping of the crust followed by thermal relaxation and crustal thinning, subsidence and gravity faulting as forcing behind depositional ‘cycle’ represented in basal Papaghni Group and overlying Chitravati Group. Repetition of the same cycle of events is identified as the cause for tilting of crust and shifting of the depositional centre to the east where the Nallamalai Group of sediments were deposited. It is proposed that subsequent subsidence- and gravity-induced block faulting produced isolated subbasins like Srisailam and Palnad where younger sediments (Srisailam Quartzite and Kurnool Group) were deposited.

Unconformably overlying the basement gneisses, Papaghni or the Chitravati Group of rocks of Cuddapah Supergroup, the Kurnool Group of rocks are exposed in two subbasins, viz. Kurnool and Palnad, and reveal mixed clastic-carbonate sedimentation mostly confined in shallow-marine domain. From limited study (Lakshminarayana et al. 1999), sediments of Kurnool lithopackage are inferred as products of alluvial fan and shallow shelf depositional setup.

4.4.2 Kaladgi–Badami and Bhima Basins

In an extensional stress regime with strong control of east-west trending normal fault systems, sedimentation of the Kaladgi–Badami basin evolved within the Dharwar craton (Fig. 4.4b). Separated by an angular unconformity, the deformed Bagalkot Group and overlying undeformed Badami Group constitute the Kaladgi Supergroup and represent sedimentation belonging to continental, transitional and shallow-marine environmental setting. From Bouguer gravity anomaly, the depth of the basin is estimated to be varying between 0.5 and 3.6 km (Vasanthi and Mallick 2006). Isolated inliers of Kaladgi rocks, termed as ‘Konkan Kaladgis’, are also reported within basalts of Deccan Trap on the west of the basin. Dey (2015) suggested cyclic sedimentation and divided the basin lithopackage in three cycles of depositional ‘Sequence’ status bounded by unconformities. According to him, each of these cycles represents a deepening-up stacking motif that initiates with conglomerate/arenite and evolves into intercalation of argillite (shale) and calcareous (limestone, dolomite) sediments/chert/BIF. From preponderance of soft-sediment deformation (SSD) structures, their traceability over large lateral domains and increase in intensity near east-west and north-south trending fault systems, earlier workers (Patil Pillai and Kale 2011) believed synsedimentary faulting and deepening to be the causative factors behind evolution and thick sediment succession of the Kaladgi–Badami basin. Chert breccias from the lithopackage are interpreted as product of diagenetic chertification of debris, formed by penecontemporaneous brecciation along synsedimentary growth faults associated with deepening of the basin (Patil Pillai and Kale 2011). From high average δ^{13} C values (3.4±0.5‰) of Badami carbonates, a primary hypersaline environment is suggested. From sediment geochemical study, Sambasiva rao et al. (1999b) proposed a mixed mafic (60%) and felsic, granitic (40%) source for the basin and suggested change in character of provenance from mafic to more felsic with evolution of the basin.

The sedimentary succession of Bhima basin (Fig. 4.4c) is exposed in narrow strips arranged in an en echelon pattern and appears to be a pull-apart basin (Dey 2015). The basin succession, classified under two formations, viz. Rabanpalli Formation (conglomerate, arenite and shale) and overlying Shahabad Formation (calcareous sediments), presents continental to shallow-marine deposition (Kale and Peshwa 1995). From δ^{13}C (+1.3 to +4.0‰) and δ^{18}O (22–26‰) values and low ^{87}Sr/^{86}Sr ratios of Shahabad limestone, Kumar et al. (1997) proposed a pre-Sturtian age (>740 Ma) for the basin. In a recent study on carbonates of the Shahabad Formation involving trace, rare-earth and C-O isotope systematics, Absar et al. (2019) observed (1) high positive values of δ^{13}C and (2) high negative cerium (Ce) anomaly and suggested burial of a large fraction of organic carbon in course of deposition of Bhima carbonates in a well-oxygenated water column. A tectonic model involving dextral transtensional movement along NW–SE trending fault (Wadi fault) and movement along associated east-west trending gravity fault is proposed (Kale and Peshwa 1995) to explain rectilinear sag in the basin. Other workers, however, favoured sinistral motion along a major NE–SW trending curved strike-slip fault as cause for basin subsidence. According to him, the present basin disposition is an artefact of post-depositional strike-slip motion in a transtensional regime.

4.4.3 Pranhita–Godavari (PG) Valley

The Pranhita–Godavari (PG) valley (Fig. 4.4d) presents an ~450 km long NW–SE trending regional lineament at the margin of the Bastar and Dharwar cratons (Chaudhuri and Deb 2004). The valley records history of recurrent rifting from Proterozoic onward. The pre-Gondwana (i.e. Proterozoic) rifting record is preserved in an ~6 km thick lithopackage, termed as the Godavari Supergroup, exposed in two linear belts (Eastern and Western Belt) flanking the Gondwana rocks. King (1881) subdivided the Supergroup into two Series on the basis of two regional-scale unconformities, viz. the Upper Transition Series and overlying Sullavai Series. Subsequently, Chaudhuri (2003) designated the lithopackage as a ‘megasequence’ and subdivided it into three depositional cycles of first or second order affinity, viz. Pakhal, Penganga and Sullavai, on the basis of regional unconformities. A wide variation in the pattern of accommodation generation and spatiotemporal sedimentation motif is noticed between the depositional cycles. Smaller-order unconformities allowed further subdivision of each cycle as ‘Subgroup’, e.g. the bottommost cycle, represented by the Pakhal Group of rocks, subdivided into Mallampalli and Mulug subgroups; the Somanpalli Group is considered as coevally evolved deep water equivalent of shallow-marine Mulug subgroup (Chaudhuri et al. 2012). Deposits belonging to shoreface and shelf depositional regimes are also described from rocks of the Somanpalli Group (Saha and Ghosh 1998). $^{40}Ar/^{39}Ar$ glauconite plateau ages from Mallampalli, Mulug and Somanpalli sandstones have yielded ages of 1686±6 Ma, 1565±6 Ma and 1620±6 Ma, respectively. Considering possible loss of Ar on deep burial of sediments, an age older than 1600 Ma is suggested for the initiation of the Proterozoic sedimentation in the PG valley (Saha and Patranabis-Deb 2014).

The second unconformity-bound cycle, exposed in the central and northern parts of the valley, is represented by the Penganga Group comprised of mixed carbonate–siliciclastic lithology. $^{40}Ar/^{39}Ar$ date of glauconite from carbonate allowed to assign a minimum age of 1200 Ma for the initiation of Penganga carbonate sedimentation. Based on age estimation, previous workers (Conrad et al. 2011; Saha and Patranabis-Deb 2014) have drawn correlation of Penganga succession with Chandarpur and Raipur successions of Chhattisgarh Supergroup of Bastar craton. From variations in stromatolite growth pattern in Penganga carbonate succession, Sarkar and Bose (1992) described a transition from basin plain to near shore subtidal across a reef.

Unconformably overlying rocks of the Penganga Group, Mulug subgroup or Mallampalli subgroup, red feldspathic sandstones of the Sullavai Group belonging to fluvial and aeolian erg depositional systems represents the third cycle. In this backdrop, correlation of the Albaka Group, unconformably overlying the Somanpalli Group and represented by siliciclastic tide-storm dominated lithopackage, remains tentative and has been correlated with either the Penganga Group or the Sullavai Group.

4.5 Lesser Himalaya (LH)

The Lesser Himalayan (LH) succession represents extrapeninsular counterpart of Proterozoic successions present in northern part of Indian peninsula (Fig. 4.1). Bounded between the Main Boundary Thrust (MBT) and Main Central Thrust (MCT), Lesser Himalayan sediments range in age from Paleoproterozoic to Cambrian. The Paleo- to Mesoproterozoic LH package (i.e. Berinag, Damta and Tejam Groups) is separated from the Neoproterozoic to Cambrian packages (Jaunsar and Mussoorie Groups) by Tons Thrust and is subdivided into Inner and Outer Lesser Himalaya, respectively. Apart from lithological description and broad environmental overview (Ghosh 1991), detailed process-based environmental interpretations are still awaited for these sediments. Age constraints for the Outer lesser Himalaya (OLH) are relatively well established. The Jaunsar Group is considered to be Neoproterozoic in age due to its occurrence below the Mario-aged (~635 Ma) diamictite of Blaini Formation of Mussoorie Group (Jiang et al. 2003). The Krol-Tal Formations of the Mussoorie Group are considered as Ediacaran-Cambrian in age (Kaufman et al. 2006; Hughes et al. 2005). However, age constraints for the Inner Lesser Himalayan sediments are very sparse. Miller et al. (2000) reported an age of

1840±16 Ma from Larji-Kullu-Rampur window of Berinag Group. Age of carbonate-dominated Deoban Formation of Tejam Group of ILH is debated and variably estimated as of Ediacaran–Cambrian (Azmi and Paul 2004), early Neoproterozoic (Richards et al. 2005) or Mesoproterozoic (Tewari and Sial 2007). ILH, however, can be convincingly distinguished from the OLH by geochemical and geochronological differences; ILH yields relatively more negative Nd values (Ahmad et al. 2000; Richards et al. 2005) and contains no detrital zircons younger than 1.6 Ga (De Celles et al. 2004; McKenzie et al. 2011), whereas strata of OLH contain abundant younger zircons (1.0 and 0.5 Ga) with relatively less negative εNd values (Ahmad et al. 2000).

Depositional history of LH is modelled in terms of both passive margin and active continental margin setting. The passive margin concept is based on detrital zircon age spectra of younger (Cambrian) rocks (Tal Group) from the Outer Lesser Himalaya (OLH), since these ages match well with that of the Greater Himalaya (GH) and Tethyan Himalaya (TH). However, it has also been reported that the OLH and GH were juxtaposed during the early Palaeozoic Pan-African orogeny. The young OLH rocks also have resemblance with the Palaeozoic Phulchowki Group of TH. It is, therefore, suggested that the Palaeozoic rocks tectonically travelled from the Tibetan to Tethys Zone by thrust nappe tectonics. Alternatively, a 1780–1880 Ma collisional arc is proposed (Kohn et al. 2010) from (1) the presence of widespread felsic igneous and volcanic rocks along a curvilinear belt across the length of Proterozoic Inner Lesser Himalaya (ILH), (2) mineralogical and geochemical characterisation of the metasedimentary rocks that differ from typical shales and point towards a volcanogenic source and (3) trace element geochemistry of mafic and felsic rocks showing arc character. However, the absence of Proterozoic metamorphic ages cast doubt on collisional tectonics. Both models considered sediments of the LH sourced from the interior of the Indian cratons.

4.6 Tectonic Models for Proterozoic Basins

Traditionally, intra- to epicratonic basin model with slow, steady subsidence is proposed to explain kilometres-thick Proterozoic basin successions with pervasive shallow-marine signatures (Ramakrishnan and Vaidyanadhan 2010). In the last two and half decades, detailed facies mapping, recognition of products belonging to different sedimentary environments, documentation of facies stacking motif from shallow to deeper parts of basin, tracing of ‘Sequence’ boundaries through space and time and application of geochemical tracers (e.g. εNd) from source to sink have allowed workers (Chakraborti et al. 2007; Patranabis-Deb and Chaudhuri 2008) to propose many other models including foreland, rift, passive margin sag basin etc.; although none of these models have found universal acceptance. Nonconformity of data received from different lines of investigation, viz. geophysical, field-based, geochemical (εNd, major element etc.) etc., prompted workers to propose different models, often not in tandem, for example, a plethora of models available for the

Vindhyan basin that ranges from epeiric (Murti 1987) to early rift followed by sagging (Bose et al. 1997) or foreland (Chakraborti et al. 2007) based on different lines of study. Similar is the case for the Chhattisgarh basin for which opinions vary between intracratonic sag (Das et al. 1992), rift (Patranabis-Deb and Chaudhuri 2008) and foreland (Chakraborty and Paul 2014). The Cuddapah basin is also no exception since two competing hypotheses on basin initiation, viz. (1) foreland (Singh and Mishra 2002) and (2) deep-seated basin-margin fault systems and mantle-induced thermal perturbation (Chaudhuri et al. 2002), are proposed to explain observed seismic and Bouguer anomaly patterns. None of these models, however, satisfy all lines of evidence, neither any of these models could address driving mechanism of basins in space-time frame (cf. Basu and Bickford 2015).

4.7 Opening and Closing of Basins

Based on relative order of superposition, stromatolite biostratigraphy and lithological similarity, the Proterozoic basin successions are assigned a broad time frame from Paleoproterozoic to Neoproterozoic (Chakraborty et al. 2010; Meert et al. 2010; Meert and Pandit 2015; Basu and Bickford 2015 and many others). Necessity for more robust age control was felt since late 1990s of last century with (1) claim of purported multicellular life (Seilacher et al. 1998) and animal body fossil as early as in early Mesoproterozoic from the lower part of the Vindhyan succession and (2) requirement of precise age control for reconstruction of Precambrian 'supercontinent' architectures.

Figure 4.5 summarises available geochronology data obtained in recent times from the cratonic basins. From U–Pb (ID-TIMS) baddeleyite age of a basic dyke intrusion in lower part of the Cuddapah Supergroup, Dharwar craton, French et al. (2008) estimated initiation of the Cuddapah basin at least 1900 Ma ago but not earlier than 2000 Ma (Basu and Bickford 2015). From the Bijawar basin, Bundelkhand craton, the Dargawan sill has yielded dates of 1789±21 Ma, 1691±180 Ma and 1967±140 Ma by Rb–Sr systematics (Haldar and Ghosh 2000; Pandey et al. 2012). Summarisation of geochronology data from the Vindhyan basin (U–Pb TIMS, Ray et al. 2002; Rasmussen et al. 2002, Pb–Pb dating of carbonate, Sarangi et al. 2004) suggest sedimentation in the basin started prior to 1721 Ma. From ^{40}Ar–^{39}Ar glauconite ages of Mallampalli sandstone of Pranhita–Godavari basin in the Dharwar craton (Conrad et al. 2011) and Albaka basin in the Bastar craton, Chaudhuri et al. (2012) surmised opening of the basin around 1700 Ma. Zircon (U–Pb SHRIMP) and Monazite (Sm-Nd CHIME) dating from a tuffaceous unit present at the basal part of Singhora Group of Chhattisgarh Supergroup allowed workers to suggest initiation of Chhattisgarh sedimentation around 1450 Ma ago (Das et al. 2009; Bickford et al. 2011b). Comparable ages were also obtained from Khariar (1455±47 Ma, Das et al. 2009) and Ampani (1446±21 Ma; Das et al. 2015) basins to suggest that either a master basin or a string of coeval basins of varied dimensions opened around 1450–1500 Ma in the eastern margin of the Indian craton.

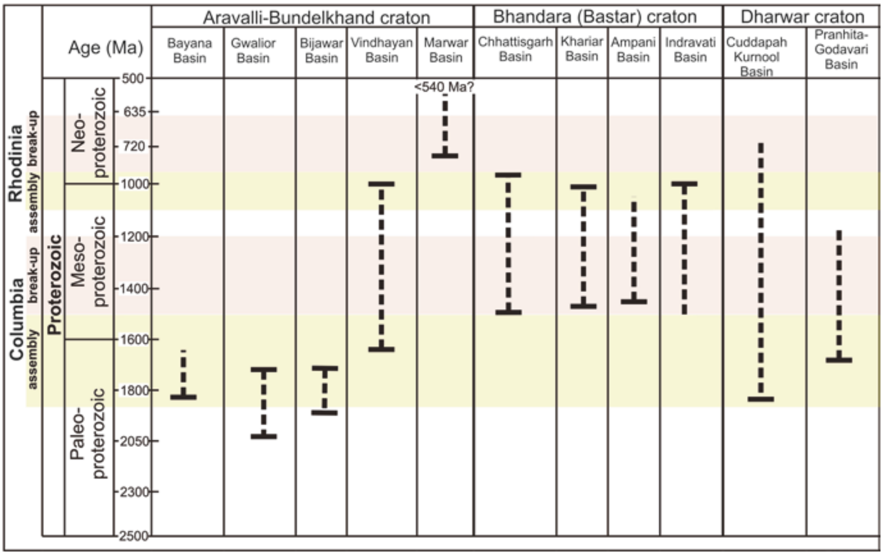

Fig. 4.5 Proterozoic cratonic basins of India in the backdrop of depositional time frame (opening/closing) and supercontinent cycle (amalgamation and breakup)

A significant number of geochronological data have also been generated in recent time to suggest closing of these cratonic basin successions. These studies have indeed placed the Neoproterozoic time frame for many of these basins, viz. Vindhyan and Chhattisgarh into the background (Patranabis-Deb et al. 2007; Malone et al. 2008; Das et al. 2009; Bickford et al. 2011a, b and many others), and established their Mesoproterozoic time frame on a strong basis. Detrital zircon geochronology and paleomagnetic evidence from uppermost Vindhyan sequence, i.e. the Rewa and Bhander Formations, allowed Malone et al. (2008) to argue for closing of the basin between 1000 and 1070 Ma. Analogous data were also obtained by Patranabis-Deb et al. (2007) from the Chhattisgarh basin, when they reported 990–1020 Ma age zircon grains from a tuffaceous layer present in the upper part of the basin succession, exposed near the Sukhda area. Subsequently, from dating (U–Pb SHRIMP zircon) of another correlative tuffaceous layer (Dhamda tuff), Bickford et al. (2011) suggested 993±8 Ma age and put forward ~1000 Ma closure age of the basin. From youngest detrital zircons of 541 Ma (U–Pb; ICP MS/SHRIMP) present in a sandstone bed in the uppermost part of the Marwar succession, Mckenzie et al. (2011) concluded closure of the basin around 520 Ma, straddling the Precambrian–Cambrian boundary. Although no body fossil is reported from the Marwar succession, several workers (Kumar and Pandey 2008; Kumar and Ahmad 2014) reported trace fossils from sandstones of the Nagaur Formation, claimed to be produced by trilobites of early Cambrian affinity. Based on the presence of nearly similar fossil assemblage of possible Ediacara affinity, Bhima and Kurnool basin successions are also correlated with the Marwar succession (Sharma and Shukla 2012). However, the correlation of Ganurgarh shale, Nagod limestone or Sirbu shale of the Upper

Vindhyan with Marwar, Bhima or Kurnool successions, as suggested previously (Basu and Bickford 2015) based on putative fossil resemblance, seems untenable following detrital zircon dates obtained by Malone et al. (2008) from topmost sandstone interval of the Vindhyan succession.

From the above discussion, it becomes apparent that among the Proterozoic cratonic basins, the Cuddapah basin is the earliest to open ~1.9 Ga before present and the Marwar basin is the youngest with possible presence of Precambrian–Cambrian transition. Most Indian cratonic basins, however, are of Mesoproterozoic age (1600 Ma to 1000 Ma), the time frame that otherwise is termed 'Boring billion' in global context in view of invariant carbon isotope data (Planavsky et al. 2015).

4.8 Role of Microbial Mat in Proterozoic Siliciclastic Sedimentation

Microbial/algal role in Proterozoic carbonate sedimentation, in particular, behind growth of stromatolites and algal laminites in varied structure and form, is well known in literature for long. Additionally, the last decade has experienced an overwhelming addition of microbial mat record in Precambrian siliciclastics, a sizeable portion of which are reported from the Indian cratonic basins (Sarkar et al. 2004; Eriksson et al. 2010; and many others). The microbial mat left records in the form of various bizarre structures, popularly known as 'mat-induced sedimentary structures' (MISS; 2001) or 'mat-related structures' (MRS; Eriksson et al. 2010). Microbially induced sedimentary structures (MISS) like petee ridges, sandcracks, gas domes, multidirected ripples, reticulate surfaces, sieve-like surfaces, wrinkle structures, roll-up structures, patchy ripples and setulf are described in literature from different Indian cratonic basins, viz. Vindhyan, Chhattisgarh, Khariar, Marwar and Cuddapah (Fig. 3 of Sarkar et al. 2014), among which most exquisite examples came from Vindhyan and Marwar basin successions. Because of the ubiquity of microbial mats across a broad range of environments, the mere presence of mats has limited value for the assessment of paleoenvironment. In Precambrian basins, however, this problem is largely mitigated by the lack of bioturbation that allows much better preservation of all types of sedimentary structures including those related to mat-sediment interaction. Further, it is also believed that the prolific non-uniformitarian mat growth in the Precambrian also performed a key role in the 'Sequence' development in course of Proterozoic basin filling history. The fact that Proterozoic sequences generally lack well-developed transgressive systems tracts (TSTs) and, instead, is dominated by stacked prograding and aggrading 'normal regressive'/highstand systems tracts (Chakraborty et al. 2012) is considered as an artefact of prolific microbial mat growth and reduced effects of wave and current reworking by organic binding of clastic particles.

4.9 Glimpses on Proterozoic Hydrosphere

One outstanding topical issue in Precambrian chemical sedimentology, debated strongly in recent time, is the redox state of deep ocean since multiple claims of contrasting character are available in literature, viz. oxic (Holland 1984), sulphidic (Canfield 1998) or suboxic (Tang et al. 2016). Very little data are available from Indian basins in this perspective. Crosby et al. (2014) reported the presence of chemolithotrophic iron-oxidising bacteria from ~1.7-Ga-old stromatolitic phosphorites of Jhamarkotra Formation of Aravalli Supergroup and suggested oceanic condition similar to modern ocean, i.e. oxygenated waters overlying reducing setting. This idea, however, did not get support from other studies. Working on Banded Iron Formation (BIF) from late Paleoproterozoic (1.78 Ga) Morar Formation of Gwalior basin, Paul (2017) noted (1) dominant hematite mineralogy, (2) the rare presence of sulfide in association, (3) the absence of any significant negative Ce anomaly and (4) very low to low concentration of Mn. Although the study compared small negative Ce anomaly within Gwalior BIFs with Ce anomalies reported from sulfidic waters of the Black Sea, from rare presence of sulfides and from dominant hematite mineralogy, it also argued that a suboxic condition (dissolved O_2 below ~0.2 µmol/l and no dissolved sulfide) prevailed in shallow subtidal environments of late Paleoproterozoic Gwalior Sea. The scenario undergoes change in Mesoproterozoic Ocean. From heavy $\delta^{34}S$ (>+25‰) values of sedimentary pyrites from the Vindhyan (Bijoygarh Shale), Chhattisgarh (Charmuria Limestone) and Cuddapah (Cumbum Shale and Narji Limestone) basins, Sarkar et al. (2010) hypothesised sulphidic anoxic deep ocean in Mesoproterozoic when very low concentrations of marine sulphate, bacterially reduced in closed systems, produced $\delta^{34}S$ values in pyrites similar to or even heavier than marine sulphate.

4.10 Discussion

Architectural models of Precambrian supercontinents, as suggested by workers (Zhao et al. 2002; Hou et al. 2008 and many others), hinged principally on geochronological data suggesting tectonometamorphic events in orogenic belts, stabilisation of cratons, post-stabilisation intrusive events including mafic dyke swarms and history of initiation and closing of sedimentary basins developed on stabilised cratons. Since 'supercontinent' models of Proterozoic Eon consider Peninsular India as an integral part of three successive configurations, viz. Expanded Ur, Columbia and Rodinia (Zhao et al. 2003; Hou et al. 2008), it may be pertinent to relate global-scale variations in eustasy and formation of sedimentary basins either with large-scale extension in rift valleys/aulacogens or with compression in forelands/subduction margins in course of fragmentation and collision of continents (Reddy and Evans 2009). Available geochronology data suggest cratonisation of continental blocks, viz. Aravalli-Bundelkhand, Eastern and Western Dharwar, Bastar and Singbhum and their amalgamation in Peninsular India at about 2.5–2.6 Ga (Meert et al. 2010). Hosted within these cratonic nuclei, unmetamorphosed and nearly undeformed sedimentary basins hold critical importance of high-resolution geochronology in understanding the evolution of ancient supracrustal stratified successions in the backdrop of ‘supercontinent’ cycle. This issue has been significantly addressed in North America, Australia and, to a large extent, China; Indian basins started getting attention only in last one and a half decade. Available data suggest that the Indian cratonic basins evolved between late Paleoproterozoic and late Neoproterozoic, in some cases straddling the Precambrian–Cambrian boundary (the Marwar basin) (Fig. 4.5).

In this backdrop, classification of Indian Proterozoic basins by Meert et al. (2010), i.e. Paleo- to Mesoproterozoic phase, early Neoproterozoic phase and late Neoproterozoic phase; Meert and Pandit (2015), i.e. Purana I, II and III; and Basu and Bickford (2015), i.e. the oldest set (2 Ga to >1.4 Ga), the largest set (~1.5 Ga to 1.0 Ga) and the youngest set (<750 Ma to ~520 Ma), looks promising (Fig. 4.6). Classifications attempted are based principally on perception of different workers rather than on correlation of basin geochnology data with underpinning crustal-scale

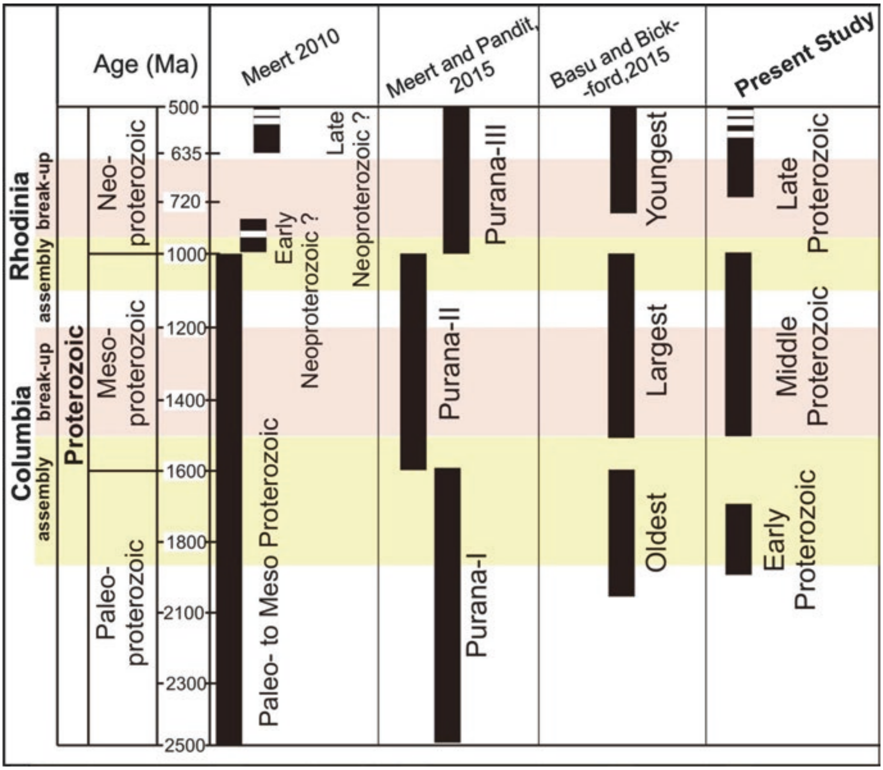

Fig. 4.6 A comparative view on classification schemes adopted by different workers. Note the scheme proposed in the present work in view of mismatch between earlier proposed schemes

events at different time frame through the Proterozoic Eon, the only exception being Meert and Pandit (2015) where these authors made an early attempt to correlate initiation and closing of basins with 'Supercontinent' cycle. It is, however, intriguing how time divisions for basin classification propsoed by these workers, i.e. Purana-I (2.5 to 1.6 Ga), Purana-II (1.6 to 1.0 Ga) and Purana-III (Neoproterozoic–Cambrian), coincided one to one with geochronologic subdivisions (Eras) of the Proterozoic Eon.

The supercontinent 'Columbia', recognised as the first true supercontinent, is formed by peak collisional tectonics between 1.95 and 1.85 Ga and remained as a quasi-integral continental lid until 1.3 Ga (Roberts 2013). As discussed, Meert and Pandit correlated opening and closing of Aravalli and Delhi Ocean basins with formation and breakup of supercontinent 'Columbia'. From ~1575 Ma post-orogenic Vellaturu granite in multiply deformed Nallamalai Fold Belt, it is surmised that deformation events in the orogen spanned between late Paleoproterozoic and early Mesoproterozoic. Since late Paleoproterozoic (2–1.8 Ga) orogens, viz. Trans–Hudson, Penokean, Thaltson–Thelon and Wopmay in North America, Kola-Karelia and Volhyn-Central Russia, and Pachelma orogens in Baltica, the 2.1–2.0 Ga Transamazonian and Eburnean orogen in south America and West Africa, 2.0–1.9 Ga Capricorn orogen in Australia, Limpopo belt in south Africa etc. from nearly every continental block are identified as signature for final assembly of supercontinent 'Columbia' (Rogers and Santosh 2002), it is tempting to relate Nallamalai Fold Belt and Nellore Schist Belt in the same bracket. The evolution of the Cuddapah basin in a peripheral foreland moat in association with evolution of the Nallamalai Fold Belt may not be an out-of-place thinking although an alternative rift model is also available. The Paleoproterozoic rift basins fringing the Aravalli-Bundelkhand craton, viz. Gwalior, Bijawar and Bayana basins, or demarcating the margin between Dharwar and Bastar cratons, i.e. the Pranhita–Godavari basin, may possibly be results of failed fragmentation attempts of the 'supercontinent' along margins of different cratonic nuclei (Fig. 4.7). It is argued from paleomagnetic and other geological evidences that despite numerous breakup attempts supercontinent 'Columbia' remained quasi-integral except for some differential plate motion in post-1.3 Ga that led to the formation of next supercontinent 'Rodinia' around 1.1–0.9 Ga.

From geochemical affinity and contemporeneity in geochronology data from highly siliceous tuffaceous units present in the basal part of Chhattisgarh, Khariar and Ampani basin successions, Das et al. (2015) postulated operation of a volcanic arc system at the eastern Indian craton margin at the time of initiation of these basins around 1450 Ma. It is worth mentioning that He et al. (2009) also reported intermittent volcanic pulses at 1.78 Ga to 1.75 Ga and 1.65 Ga to 1.45 Ga at the southern margin of the North China craton, interpreted the Xiong'er volcanic rock as evidence for a continental margin volcanic arc system and correlated the subduction-related outgrowth of continents with the formation of accretionary zones along the margins of Laurentia, Amazonia and Australia during the time frame encompassing the last phase of the Columbia supercontinent (Bauer et al. 2003). Hence, it is reasonable to assume a similar volcanic arc system at the eastern cratonic margin of India as a part of the global-scale accretionary zones of an out-

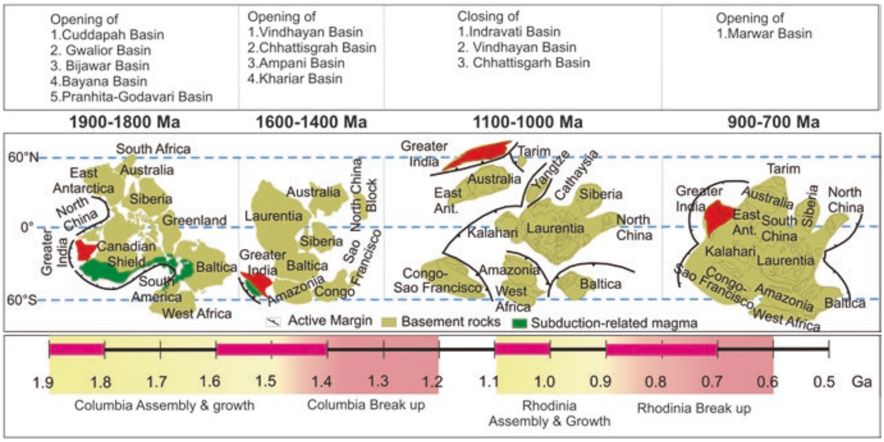

Fig. 4.7 Cartoon illustrating correlation of Proterozoic basin opening and closing of Peninsular India in the backdrop of amalgamation and fragmentation of supercontinents 'Columbia' and 'Rodinia'. Note prevalence of geochronological dates of 1900–1800 Ma, 1600–1400 Ma, 1100–1000 Ma and 900–700 Ma in Indian basins

sized arc at c. 1450 Ma (He et al. 2009), the signature of which is preserved on all major neighbouring continents, viz. North China, Australia, East Antarctica and North America. However, from the occurrence of aligned, deformed alkaline complexes, tholeiites and carbonatites, Upadhyay et al. (2006) interpreted Mesoproterozoic rifting around 1480±17 Ma at the boundary of eastern Ghats belt (EGB) and Bastar craton. Although signatures of extensional tectonics cannot be denied in the presence of alkaline and related igneous rock suites, it is also clear that overall compressional tectonics was operative at the eastern margin of the Indian craton. Evidences of concomitant extension and compression are well documented by Zhao et al. (2003) from supercontinent 'Columbia'.

The ~1000 Ma closing of basins, viz. Vindhyan (Malone et al. 2008), Chhattisgarh (Patranabis-Deb et al. 2007) and Indravati (Mukherjee et al. 2012), irrespective of their host cratonic nuclei, possibly bear indication of a major crustal-scale event associated with amalgamation of supercontinent Rodinia. Indeed, from correlation of tuff layers from the uppermost part of Chhattisgarh and Indravati basins, Mukherjee et al. (2012) suggested an ~1000 Ma rhyolitic flare-up related to the assembly of Rodinia and docking of India and East Antractica. Further, Li et al. (2008) postulated episodic plume events at 825 Ma, 780 Ma and 750 Ma and continental rifting in supercontinent Rodinia following its amalgamation. From paleomagnetic study and U–Pb ages, Torsvik et al. (2001) correlated 771±5 Ma old (Gregory et al. 2009) Malani Igneous suite with granitoids and dolerite dykes of Seychelles microcontinent and thereby postulated plate dynamics of Rodinia breakup and Gondwana assemblage. Subsequent to rifting and outpouring of Malani igneous suite (MIS), the westerly dipping Marwar basin opened on the northwestern flank of the Indian craton.

4.11 Future Goals

1. At the present state of knowledge, correlation of basins and their connectivity to Proterozoic crustal-scale events related to 'supercontinent' amalgamation and breakup are still tentative in absence of high-resolution, robust data from all cratonic basins of peninsular India. Although the present work admits significant progress in recent time, it also argues for generation of more data to back conjectures of connectivity of basin opening and closure with 'supercontinent' history. Definitely classification of Proterozoic basins requires further high-resolution geochronological work in the backdrop of identification of crustal-scale events, going beyond simplified classification based on Proterozoic chronostratigraphy.
2. Another important parameter to constrain basins with 'supercontinent' cycle is paleomagnetic signatures from the basin successions. Some important data are generated in recent time, that is, more data need to be generated.
3. Oxygenation of atmosphere and hydrosphere is a topical issue. Despite the presence of basins spanning between late Paleoproterozoic and late Neoproterozoic in Indian craton and occurrence of redox-sensitive chemical sediments (BIF, phosphorite, pyrite, barite etc.) within the basin successions, very little data are available. Systematic studies of these chemical sediments with employment of redox-sensitive isotopic systematics (Cr^{54}, S^{33}, Se etc.) may provide important clues regarding ocean chemistry in the early part of the earth's history.
4. The presence of Precambrian–Cambrian boundary is a big debate from available studies of Indian cratonic basins. Paleontological study claiming the presence of Ediacaran fossil assemblage, carbon $(\delta^{13}\ C)_{carbonate}$ isotope proxy indicating evidence of glaciation, field evidence indicating undoubted glaciation or geochronology data with use of robust systematics has not been found to be in tandem from any of the basin successions in order to establish the boundary from Peninsular India on a firm basis. The present work voices the necessity of multiproxy studies in cratonic basins to resolve the issue.

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