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Santanu Banerjee
Subir Sarkar *Editors*

Mesozoic Stratigraphy of India

A Multi-Proxy Approach

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We dedicate this book to Prof. Pradip K. Bose

Series Editor Foreword

Mesozoic sedimentary sequences of India were deposited in intra-cratonic and pericratonic tectonic basins, and sensitively recorded palaeoclimatic changes and ocean–land life. The pile of almost undisturbed Mesozoic sediments is punctuated by marine transgression–regression events and are most suitable for sequence stratigraphic studies. Sedimentation under the influence of tectonism, plate movement and climatic variability ended with a well-known mass extinction event leading to the demise of gigantic dinosaurs. The large parts in Central India are covered by Deccan lava flows obscuring the infratrappean geological set-up. Economic petroleum resources within Mesozoic sequences make them so important.

Owing to excellent palaeontological records, some of the basins like Kutch, Jaisalmer, Spiti and Cauvery were extensively studied. The dinosaur fossil hunting grounds of Mesozoics are a paradise for vertebrate palaeontologists. The evidence of K/Pg mass extinction and outburst of basaltic lava covering a large part of the geology of India are significant global events. The Gondwana Mesozoic sedimentary basins are another thick largely continental sediments affected by tectonism. The geological datasets obtained from Gondwana sediments are of international significance. I hope this book on the Mesozoic stratigraphy of India employing various proxies will bring out new results and open new vistas. I sincerely thank editors and contributors for bringing out this volume.

Series Editor
Lucknow, India Satish C. Tripathi

Preface and Acknowledgements

Mesozoic sedimentary rocks of India record the effects of abnormal sea level rise, greenhouse climate, intensified volcanism, hypoxia in seawater and extensive black shale deposition. Mesozoic time also witnessed the mass extinction events, the evolution of dinosaurs and the breakdown of the supercontinent Pangea, followed by the formation of Gondwana. The Mesozoic record is particularly significant for the industry as more than 75% of oil and gas formed during this time. The Mesozoic record of India has been investigated thoroughly from biostratigraphic and lithostratigraphic viewpoints in the last century. Literature survey, however, reveals significant gaps in knowledge regarding sedimentology, sequence stratigraphy, chemostratigraphy and some major geological events during the Mesozoic. This book envisages a multi-proxy approach using detailed sedimentological analysis, floral and faunal assemblage, geochemical proxies, magnetic susceptibility, stable isotopes and associated biotic events for paleoclimatic and the paleoenvironmental interpretations of the Mesozoic sedimentary record of India. The book focuses on recent findings on lithostratigraphy, chemostratigraphy, biostratigraphy, magnetostratigraphy and sequence stratigraphy of Mesozoic basins of India, including Kutch, Cauvery, Krishna-Godavari, Jaisalmer and Narmada basin and Spiti valley. The edited volume highlights the present understanding regarding stratigraphical and depositional histories of Mesozoic sedimentary basins in the backdrop of global tectono-thermal events and sea-level changes. A thorough biostratigraphic investigation of the sedimentary deposits provides high-resolution interpretations of the Mesozoic basins. A synthesis of sedimentological, palaeontological and chemical data using the multiproxy approach provides a comprehensive understanding of the Indian Mesozoic record to the students, researchers and professionals. Information presented in this book not only benefits academicians but is also relevant for the oil and gas industry.

This book comprises 23 chapters covering most of the Mesozoic sedimentary basins in the peninsular and extra-peninsular regions of India; more than half of which are from Kutch, Cauvery and Jaisalmer basins. The first two chapters of this book present reviews of stratigraphy, sedimentation history and paleogeography of Mesozoic basins in India. The first chapter "A Review of Stratigraphy, Depositional Setting and Paleoclimate of the Mesozoic Basins of India" (Dasgupta) reviews the current understanding of the Mesozoic basins, and the second "Cretaceous Deposits of India: A Review" (Chakraborty et al.) provides a thorough review of stratigraphy, paleoclimate and paleogeography of Cretaceous sedimentary basins. The third chapter "Radiation of Flora in the Early Triassic Succeeding the End Permian Crisis: Evidences from the Gondwana Supergroup of Peninsular India" (Ghosh et al.) presents the radiation of flora after the Permian–Triassic mass extinction event (PTME). The stratigraphy of the Kutch is debated over the years for the consideration of lithostratigraphic and chronostratigraphic aspects. In this book, we have retained both classification schemes so that scientific issues are under focuss rather than stratigraphic jargons. The fourth chapter "An Overview of the Mesozoic (Middle Jurassic to Early Cretaceous) Stratigraphy, Sedimentology and Depositional Environments of the Kachchh Mainland, Gujarat, India" (Mahender) presents a classical review on sedimentology and lithostratigraphy of the Kutch Basin. The fifth chapter "Magnetic Polarity Stratigraphy Investigations of Middle-Upper Jurassic Sediments of Jara Dome, Kutch Basin, NW India" (Venkateshwarlu) presents magentostatic data for the Jhuran Formation to constrain its age between Magneto Chrons M24 and M19 of Kimmeridgian to Tithonian. The sixth chapter "Provenance and Paleo-weathering of the Mesozoic Rocks of Kutch Basin: Integrating Results from Heavy Minerals and Geochemical Proxies" (Chaudhuri et al.) integrates geochemical data and heavy mineral assemblage of Mesozoic formations in Kutch to indicate the source of sediments. The study relates possible sources of Mesozoic sediments in the Kutch Basin to Precambrian rocks of the Aravalli craton and Nagar Parkar igneous complex. The seventh chapter "Geochemistry of Callovian Ironstone in Kutch and Its Stratigraphic Implications" (Bansal et al.) presents petrographical and mineralogical investigations of Callovian golden oolites of the Jhumara Formation of Kutch Basin, and indicate a similarity in the chemical signature of Jurassic ironstones across the globe. The eighth chapter "Oxic-dysoxic Tidal Flat Carbonates from Sadara, Pachham Island, Kachchh" (Kale et al.) presents petrographical and geochemical investigations of Bathonian to Callovian carbonates of the Kutch Basin in the Pachham Island to indicate the formation of carbonates in warm seawater during the Jurassic time. The ninth chapter "Cosmopolitan Status for *Taramelliceras kachhense* (Waagen) (Ammonoidea) from Kutch, Western India" (Roy et al.) revisits the taxonomy of the genus *Taramelliceras* from the Kutch Basin and compares with the European types to understand the palaeobiogeography. The tenth chapter "Nautiloid Biostratigraphy of the Jurassic of Kutch, India: An Exploration of Bio- and Chrono-stratigraphic Potential of Nautiloids" (Halder) presents the utility of nautiloid biozonation and proposes a biostratigraphic classification of the Jurassic succession based on nautiloids. Chapter "Taphonomic Pathways for the Formation of Bioturbated Cycles in the Early Cretaceous Wave-Dominated Deltaic Environment: Ghuneri Member, Kachchh Basin, India" (Desai and Chauhan) presents the effect of storms, erosion, sedimentation on ichnofacies and ichnoassemblage. Systematic ichnological analysis indicates 24 recurring trace fossils, categorized into fair-weather and storm-weather trace fossil ichnoassemblages. Chapter "Gastropod Biozonation for the Jurassic Sediments of Kutch and Jaisalmer Basins and Its Application in Interbasinal Correlation" (Saha et al.) presents 12 biozones for Kutch and three biozones for Jaisalmer based on gastropod assemblage data. The authors demonstrate that like ammonites, the gastropods can effectively be used to establish acceptable regional biostratigraphy of both Kutch and Jaisalmer Basins. Chapter "Diagenetic Controls on the Early to Late Bathonian Fort Member Sandstone of Jaisalmer Formation, Western Rajasthan" (Ahmad et al.) presents a detailed petrographic analysis of the Bathonian sandstones in the Jaisalmer basin to establish the paragenetic sequence and porosity evolution in relation to diagenetic evolution. Chapter "Seismicity Forcing Transition from Siliciclastic to Carbonate Realm in the Thaiyat-Hamira Succession of Jaisalmer, Rajasthan" (Mandal et al.) documents soft-sediment deformation layer in between Thaiyat and Hamira Members, Jaisalmer, Rajasthan and traced and relates the seismically induced deformation to global paleotectonics recorded at different countries at the Bajocian-Bathonian transition. Chapter "Biostratigraphic Implications of the Calcareous Nannofossils from the Spiti Formation at Langza, Spiti Valley", (Singh et al.) proposes a Callovian age (part of NJ12 Nannofossil Zone) to the black shale (*'Belemnites gerardi* beds') belonging to the belemnites-rich Lower Member of the Spiti Formation based on calcareous nannofossil biostratigraphy. Chapter "Records of Marine Transgressions and Paleo-Depositional Conditions Imprinted Within Cretaceous Glauconites of India" (Bansal et al.) compares the Cretaceous glauconites of India and relate them to global sea level rise, sub-oxic shallow shelves and intensive continental weathering. Chapter "Early Cretaceous Flora from the East Coast Sedimentary Basins of India: Their Chronostratigraphic and Palaeobiogeographic Significance" (Chinnappa et al.) provides precise ages of Cretaceous formations based on biostratigraphically diagnostic palynomorphs and macroflora. The study provides precise ages to the lithounits of the east coast sedimentary basins of India based on the marker taxa. Chapter "Facies and Microfacies Analysis of Kallankurichchi Formation, Ariyalur Group with an Inkling of Sequence Stratigraphy" presents a detailed facies analysis of the fossiliferous carbonate succession of late Cretaceous Kallankurichchi Formation and distinguishes two broad facies associations, wave-dominated and tide-dominated, within the succession. Chapter "Litho-Biostratigraphy and Depositional Environment of Albian-Maastrichtian Sedimentary Succession of Cauvery Basin in Ariyalur Area" (Nagendra and Nallapa Reddy) presents sedimentological analysis, sea level cycles and paleoclimatic context of the Albian-Maastrichtian sedimentary succession of the Cauvery basin. Chapter "Continental-to-Marine Transition in an Ongoing Rift Setting: Barremian-Turonian Sediments of Cauvery Basin, India" (Chakraborty et al.) presents a thorough field-based facies analysis to document fluvial-to-marine transition in a syn-rift setting during the Mesozoic breakup of east Gondwanaland. Chapter "Stratigraphy, Sedimentology and Paleontology of Late Cretaceous Bagh Beds, Narmada Valley, Central India: A Review" (Bhattacharya et al.) presents a detailed sedimentological and paleontological account of the Mesozoic sediments in the Narmada Valley region of central India. Chapter "Fluvial Architecture Modulation in Course of Aeolian Dominance: Upper Terrestrial Member, Bhuj Formation, Kutch" (Koner et al.) presents a thorough analysis of bedforms and paleohydarulic parameters within the early Cretaceous Bhuj Formation. The study documents the evolution of fluvial channel system and overall drying-up trend through time. Finally, Chapter "Mineralogical and Textural Characteristics of Red

Boles of Western Deccan Volcanic Province, India: Genetic and Paleoenvironmental Implications" (Singh et al.) presents a detailed petrographical and mineralogical analysis of the latest Cretaceous red bole beds, interlayered with Deccan Basalt in western India. The study indicates several breaks during the eruption of Deccan Basalt, which lead to the formation of volcanic paleosol at places.

We express our sincere thanks to all the authors of this book for their valuable research contributions. We are thankful to reviewers for providing critical reviews of the submitted manuscripts. Scholars who served as reviewers for this book are Subir Bera, H. N. Bhattacharya, Ajoy Bhowmick, Abhijit Chakraborty, Nivedita Chakraborty, Adrita Chaudhuri, D. K. Chauhan, Sudipta Dasgupta, Anima Mahanta, Soumik Mukhopadhyay, R. Nagendra, Suraj K. Parcha, Deo Brat Pathak, Malek Radhwani, A. Sen, D. S. N. Raju, Debahuti Mukherjee, Tathagata Roy Choudhury, Pradip Samanta and Sanjoy Sanyal. We are thankful to Sanghita Dasgupta for proofreading manuscripts for a major part of the book.

Mumbai, India Santanu Banerjee
Kolkata, India Subir Sarkar

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About the Editors

Santanu Banerjee is a Professor at the Department of Earth Sciences, Indian Institute of Technology Bombay. He obtained a Ph.D. degree from Jadavpur University, Kolkata, in 1997. Santanu does research in sedimentology and petroleum geology. His research areas cover sedimentary facies and basin analysis, microbially induced sedimentary structures, sequence stratigraphy, recent sedimentary environments around the Gulf of Cambay for outcrop analogues of subsurface reservoirs, provenance and tectonic settings, glauconite formation in sequence stratigraphic context and Jurassic black shale in Kutch. He is the Associate Editor in Chief of the Journal of Palaeogeography. He is on the editorial board of the Arabian Journal of Geosciences, SN Applied Sciences and Journal of Earth Systems Science. He is the Vice-President of the Indian Association of Sedimentologists. He has supervised many research projects sponsored by Government agencies and oil companies. He has published more than 100 research articles in journals and edited 4 books.

Subir Sarkar is currently the Professor in the Department of Geological Sciences, Jadavpur University, Kolkata India. He obtained his Ph.D. degree from Jadavpur University in 1990. He has more than 25 years of experience in teaching and about 30 years in research. He has worked in different Proterozoic basins in India and his scientific interests are in the areas of sedimentology, sequence stratigraphy and basin analysis. With a special interest in the record of early life, he is currently studying the influence of microbial mats on Precambrian sedimentation. He is on the editorial board of the Journal of Palaeogeography. He has published more than 100 research articles in peer-reviewed national and international journals and conference proceedings. He has also published 16 book chapters and edited 4 books.

Abbreviations

ACM	Active continental margin
APWP	Apparent polar wandering path
BU	Bela Uplift
CCD	Calcite compensation depth
CEPL	Cementation porosity loss
ChRM	Characteristic Remanent Magnetization
CI	Contact index
CIA	Chemical index of alteration
CIR	Central Indian Ridge
CIW	Chemical Index of weathering
CNPS	Cretaceous Normal Polarity Superchron
COPL	Compactional porosity loss
CU	Chorad Uplift
DRM	Detrital remanent magnetization
DSDP	Deep sea drilling project
EDS	Energy dispersive spectroscopy
FA	Facies association
FAD	First appearance datum
FMS	Fort Member Sandstone
GTS	Geological time scale
HCS	Hummocky cross-stratification
HREE	Heavy rare earth element
HST	Highstand systems tract
IBF	Island Belt Fault
ICS	International commission on stratigraphy
ICV	Index of compositional variability
IGV	Intergranular volume
JMA	Jaisalmer-Mari basement arch
KG Basin	Krishna–Godavari Basin
KMF	Kutch Mainland Fault
KMU	Kutch Mainland Uplift
K-Pg boundary	Cretaceous-Paleogene boundary

KU	Khadir Uplift
LAD	Last appearance datum
LREE	Light rare earth element
Ma	Million years
MFS	Maximum flooding surface
MPS	Magnetic polarity stratigraphy
NASC	North American shale composite
NKF	North Kathiawar Fault
NPF	Nagar Parkar Fault
NRM	Natural remanent magnetization
OAE	Oceanic anoxic event
PAAS	Post-Archean Australian shale
PCA	Principal component analysis
PG Basin	Pranhita-Godavari Basin
PIA	Plagioclase index of alteration
PTB	Permian–Triassic boundary
PTME	Permian–Triassic mass extinction (PTME)
PU	Pachchham Uplift
REE	Rare earth element
RSL	Relative sea level
SB	Sequence boundary
SEM	Scanning electron microscopy
SSD	Soft sediment deformation
SWF	South Wagad Fault
SWU	South Wagad Uplift
TE	Trace element
TST	Transgressive systems tract
UCC	Upper continental crust
VGP	Virtual geomagnetic pole
VNIR	Visible-near infrared
XRD	X-ray diffraction
XRF	X-ray fluorescence

A Review of Stratigraphy, Depositional Setting and Paleoclimate of the Mesozoic Basins of India

Sanghita Dasgupta

Abstract The Indian Gondwana basins preserve a thick sedimentary deposit from Carboniferous to Cretaceous. In India, the Gondwana sediments were mainly deposited in four intracratonic basins, i.e. Pranhita-Godavari (PG), Satpura, Son-Mahanadi and Damodar essentially in a fluviatile setting. While the PG Basin preserves the most continuous sedimentary history, Mesozoic basins at the west coast, including Kutch, Barmer, Jaisalmer, Saurashtra, record sedimentation from the Jurassic period. During the Mesozoic era, there was a gradual shift in the climatic condition, which got reflected in the sedimentation pattern and fossil record. The Early Triassic sediments of the peninsular basins were deposited under warm to semi-arid climatic conditions in an essentially fluvial setting. The PG and Rewa basins record the global Triassic redbeds, having similar seasonal conditions, evidence of freshwater carbonates, along with profuse terrestrial fauna and flora. The Early Jurassic sediments of Barmer and Jaisalmer were essentially deposited in fluvio-lacustrine environment under humid climatic condition. With the advent of Middle Jurassic, limestone started depositing in the Mesozoic basins. The Middle to Late Jurassic sediments of the western coastal basins were deposited primarily in shallow marine environment. Gypsum formed under fluvio-lacustrine setting in PG and Rewa basins, while it formed under shallow marine conditions in Kutch and Jaisalmer basins. By the Early Cretaceous, oceans began to separate the major fragments of the Gondwanaland, which led to the extensive deposition of mostly marginal marine to shallow-marine sediments all along the western coastal basins of India. Whereas the Gondwana basins record a few fluvial successions, having profuse vertisol profiles. Deccan traps overlie the Mesozoic sedimentary successions of the Gondwana basins, while the Cenozoic sedimentation continues at western coastal basins. This work attempts the correlation of Mesozoic basins of India and points out areas of future research.

Keywords Depositional environment · Gondwana · Indian Mesozoic basins · Paleoposition · Stratigraphic correlation

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1 Introduction

Gondwana supercontinent broke during ~200–60 Ma, rifted, and the fragments drifted away in many directions (McLoughlin 2001; Riley and Knight 2001; Conrad and Gurnis 2003; Jokat et al. 2003). One of the fragments—the Indian Shield, drifted approximately northward and eventually collided onto the Eurasian plate, producing the spectacular trans-continental Himalayan fold-thrust belt (Norton and Sclater 1979; Reeves and de Wit 2000; Reeves et al. 2004). The break-up and northward journey immensely affected the Indian shield in several ways, including erosion at the base of its lithosphere and the development of several structural basins (Acharyya and Lahiri 1991; Veevers and Tewari 1995; Biswas 1999; Kumar et al. 2007; Veevers 2009). Before the break-up, the Gondwana supercontinent developed several sedimentary basins along the paleo-suture zones at the end of Carboniferous. A thick succession of sedimentary rocks piled up in these basins.

Several intra-continental rift structures were formed due to supercontinent break-up and rifting which acted as locations of sedimentation in association with continued tectonic activity (Biswas 1999; Veevers 2009). The term Gondwana derived from the recognition by workers at the Indian Geological Survey in the mid- to late 19th century of a distinctive sedimentary sequence preserved in east-central India (McLoughlin 2001). The Indian Gondwana basins contain a rich record of tectonic, sedimentary, paleontological and volcanic history of the Gondwanaland (Biswas 2003; Mukhopadhyay et al. 2010; Ghosh and Sengupta 2019; Bandyopadhyay and Ray 2020). The Gondwana basins of India represent about 200 Ma of the geological record of peninsular India. The initial depressions of the basins were formed due to the sagging related to the attenuation of the crust. The Lower Gondwana sedimentation started within these pre-rift sag basins over the Proterozoic basement. Subsequently, these basins remained active due to fault-guided subsidence that provided accommodation space for the younger sediments. Different types of basins formed depending on the orientation difference between the weak zones and the stress related to the regional E-W extension (Chakraborty et al. 2003; Mukhopadhyay et al. 2010). During the Mesozoic era, the Indian subcontinent had migrated from below the 30º S latitude to near the equator (Kiessling et al. 2003; Golonka 2011; Hall 2012). Throughout the Mesozoic era, climatic conditions varied as a function of overall global climatic changes and movement of the Indian subcontinent towards the equator. In the Triassic, the exposed land extended from about 85° N to 90° S. This exposed land was called the ‘Pangaea’, which came into existence during the Carboniferous due to the collision between Gondwana and Laurasia (between ~330 and 320 Ma; Veevers 2004). The continent was largely assembled by the end of Permian.

This paper integrates tectonic, sedimentological and paleontological data from a range of published sources to provide a summary of the current state of knowledge concerning the changes in the depositional environments of the basin-fill successions and evolution with respect to flora and fauna, landscape and vegetation during the Mesozoic time in India. Further, this study attempts a correlation of the Mesozoic basins. Compilation of selected references of the different Mesozoic basins of India is given in Table 1.

Table 1 A bibliography of the Mesozoic basins of India

Mesozoic Basin	Mesozoic stratigraphy	Selected references
Pranhita-Godavari	Chikiala Gangapur Kota Dharmaram Maleri Bhimaram Yerrapalli Kamthi	Goswami and Ghosh (2020), Dasgupta and Ghosh (2018), Goswami et al. (2018), Dasgupta et al. (2017), Bandyopadhyay (2011), Bandyopadhyay et al. (2010), Bandyopadhyay and Sengupta (2006), Sarkar and Chaudhuri (1992), Kutty and Sengupta (1989), Kutty et al. (1987)
Satpura	Lameta Jabalpur Bagra Denwa Pachmarhi	Sengupta et al. (2016), Ghosh et al. (2012), Dogra et al. (2010), Ghosh and Sarkar (2010), Saha et al. (2010), Prakash (2008), Ghosh et al. (2006), Wilson and Mohabey (2006), Ghosh et al. (2003, 2001), Ghosh (1997), Ghosh et al. (1995)
Rewa	Parsora Tiki Karki Pali	Bhat et al. (2018a, b), Pillai et al. (2018), Mukherjee et al. (2012), Datta (2004); Datta et al. (2004)
Kutch	Bhuj Jhuran Jhumara Jhurio	Chaudhuri et al. (2020a, b, c, d), Chaudhuri et al. (2018), Desai and Biswas (2018), Bansal et al. (2017), Mandal et al. (2016), Arora et al. (2015), Alberti et al. (2012, 2013), Biswas (2005, 1999, 1993, 1991, 1987, 1982, 1981)
Barmer	Fatehgarh Ghaggar-Hakra Lathi	Dasgupta and Mukherjee (2017), Bladon et al. (2015a, b), Dolson et al. (2015), Farrimond et al. (2015), Compton (2009)
Jaisalmer	Parh Goru Pariwar Bhadasar Baisakhi Jaisalmer Lathi	Alberti et al. (2017), Sharma and Pandey (2016), Pandey and Pooniya (2015), Pienkowski et al. (2015), Srivastave and Ranawat (2015), Mude et al. (2012), Pandey et al. (2012), Pandey and Choudhary (2010), Rai and Garg (2007), Singh (2006), Torsvik et al. (2005), Sudan et al. (2000)
Saurashtra	Wadhwan Ranipat Surajdeval Than	Khan et al. (2017), Casshyap and Aslam (1992), Aslam (1992, 1991)

2 Gondwana Basins

In peninsular India, the Gondwana sediments were mainly deposited in four intracratonic basins, i.e. Pranhita-Godavari (PG), Damodar, Satpura, and Son-Mahanadi with a distinct post-Carnian hiatus (except for the PG Basin) (Chakraborty et al. 2003). The analysis of the shape of the outcrop belt, characteristics of the basin-fill and the orientation of the associated faults relates the origin of the Gondwana basins of peninsular India to a single regional tectonic event (Chakraborty et al. 2003). The sites of basin nucleation were guided by the pre-existing zones of weakness in the Precambrian basement (Biswas 2003). Each of the major basin has been discussed below and a location map of these basins is given in Fig. 1.

2.1 Pranhita-Godavari Basin

2.1.1 Tectonics

The Pranhita-Godavari (PG) basin preserves records of repeated opening and closing of Proterozoic and Gondwana rifts (Chaudhuri et al. 2012). PG basin evolved as a NNW-SSE trending syn-rift basin. The Gondwana deposit (~4–5 km thick) is exposed as an elongated outcrop belt that is ~400 km long and ~75 km wide, surrounded by the exposures of the Proterozoic sedimentary rocks and Archean basement rocks (Biswas 2003; Chakraborty et al. 2003; Chaudhuri et al. 2012). Bouguer anomaly contours are more closely spaced near the eastern margin of the PG Gondwana basin, indicating greater accommodation of sediments towards the footwall margin of the basin over time (Narula et al. 2000; Biswas 2003; Chakraborty et al. 2003; Ghosh and Sengupta 2019). The western margin of this basin is demarcated by a number of small intrabasinal normal faults affecting the syn-rift strata. Intrabasinal normal faults are oriented at a high angle to the trend of the boundary faults. Some of these faults demarcate subordinate half-grabens within the master basin. The stratigraphically younger formations of the deposit are bound by the Godavari Valley Fault on the eastern side, which brings the upper Gondwana strata in contact with the Proterozoic rocks (Fig. 1 of Dasgupta and Ghosh 2018; Goswami and Ghosh 2020). During Permo-Carboniferous, the paleolatitudinal position (~300 Ma) of the present location of the PG Basin was below 60º S, while during Early Cretaceous (~140 Ma) the paleoposition was around 40º S (Scotese et al. 1999).

2.1.2 Stratigraphy and Lithology

The ~5 km thick, dominantly fluvial deposits that formed in the PG Gondwana Basin range in age from the Late Carboniferous to Cretaceous (Robinson 1967; Kutty et al. 1987; Kutty and Sengupta 1989; Veevers and Tewari 1995; Bandyopadhyay

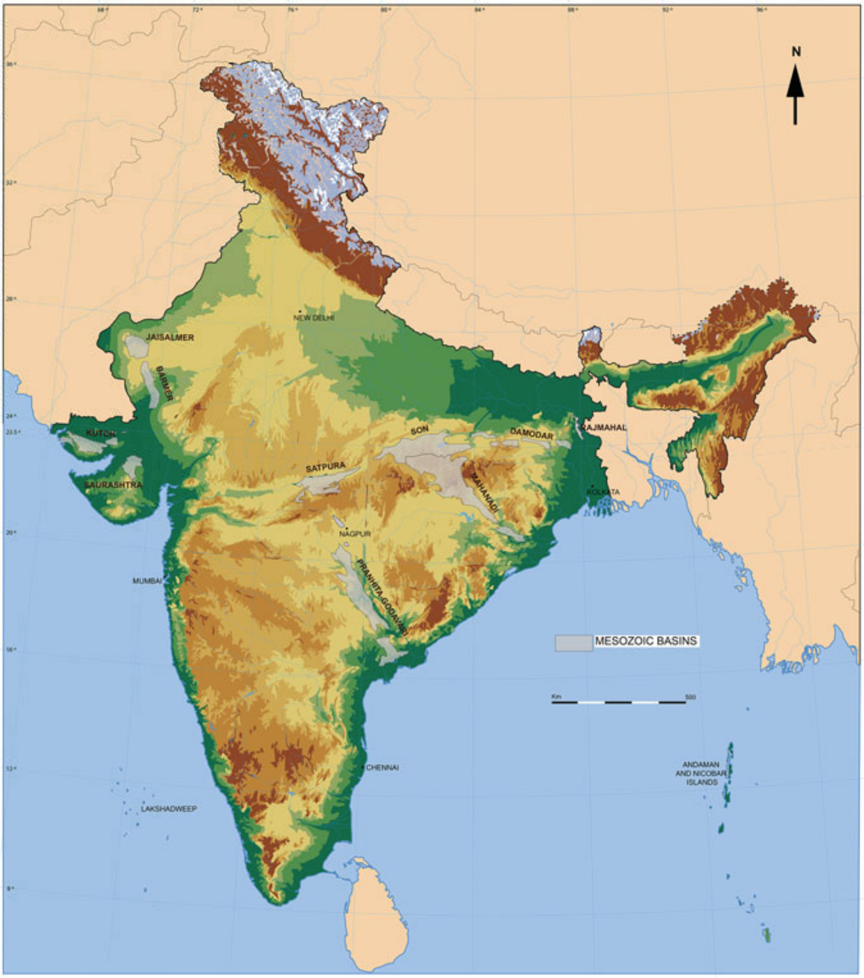
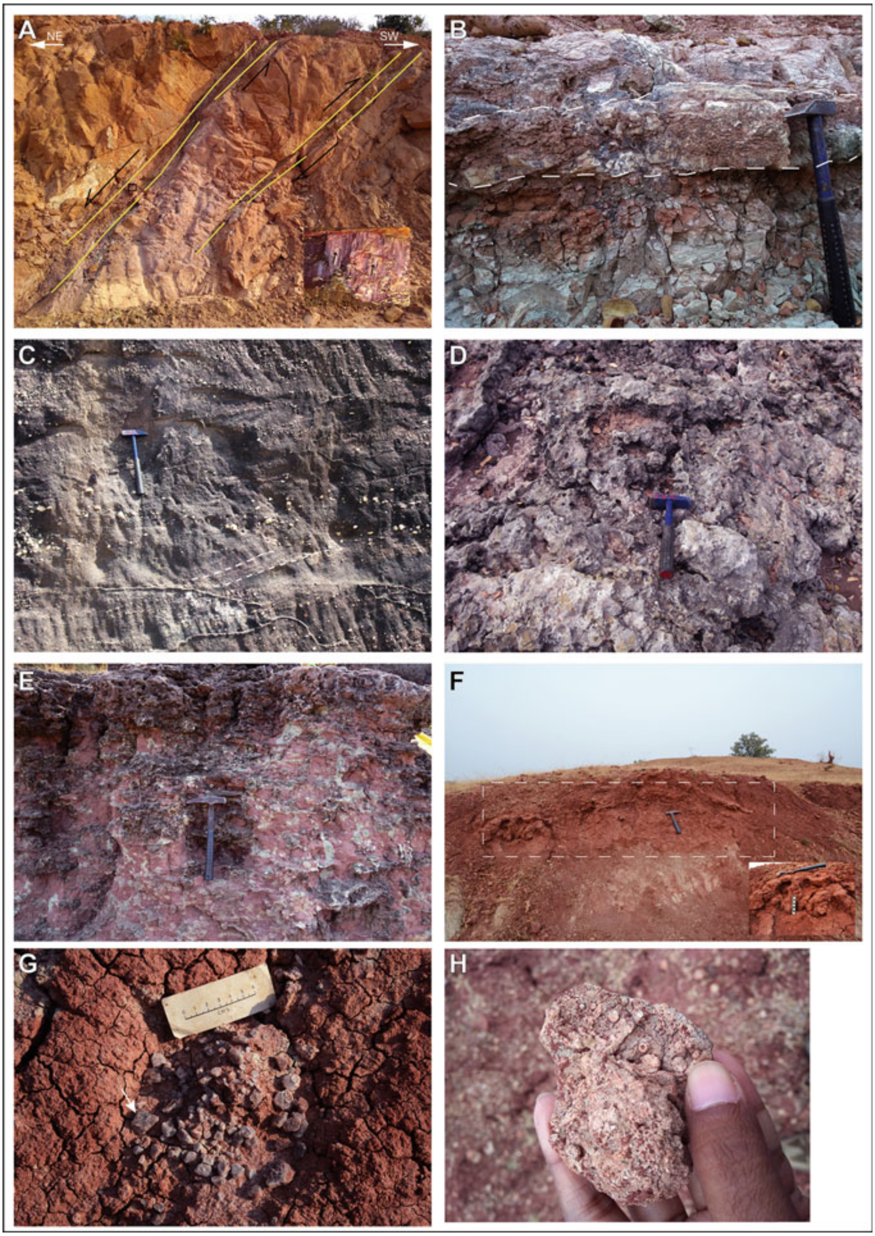


Fig. 1 Mesozoic sedimentary basins superimposed on the physical map of India (positions of sedimentary basins after Dasgupta (1975), Biswas (1991), Casshyap and Aslam (1992), Bandyopadhyay and Sengupta (1999), Farrimond et al. (2015)

2011; Dasgupta et al. 2017; Dasgupta and Ghosh 2018). Based on paleontological and lithological criteria, King (1881) subdivided the Gondwana succession into “Lower Gondwanas” and “Upper Gondwanas”. He further subdivided the Lower Gondwanas into three subunits—Talchir, Barakar and Kamthi. The lower part of the succession, Late Carboniferous to Permian, contains glaciogenic conglomerates and coal-bearing strata. The Talchir Formation crops out as a narrow strip, broken at places by faults and never attaining any great thickness, along the western margin of the basin. It consists of tillites, greenish shale and sandstone (Kutty et al. 1987; Srivastava 1992). The Barakar Formation consists essentially of the coal-bearing group of rocks that overlie the Talchir (Kutty et al. 1987; Kutty and Sengupta 1989). The 'Infra-Kamthi' Formation, as used by Bose and Sengupta (1993) was renamed as 'Kundaram Formation' by Ray (1997), and made up of shale, mudstone and thick sandstone (3–5 m). Recent observations reveal thick fault gouge (3–5 cm) of ferruginous mud at many places. The ferruginous mud shows well-preserved slickenside. The dip angle (~35°) of the fault planes (Fig. 2a) are oriented towards NE. Hence the strike of the faults is NW-SE, which coincides with the major rift faults of the PG Basin. This fault cuts across all the sedimentary strata, most likely late stage rift faults. The Kundaram Formation is overlain by the Kamthi Formation, which is composed of highly ferruginous sandstone or ironstones, numerous iron-rich concretions and purplish siltstone (Kutty et al. 1987). The Lower Gondwana is followed upwards by the Upper Gondwana formations.

The Upper Gondawanas was further subdivided into "Maleri Group", "Kota Group" and "Chikiala Group" by King (1881), and later these groups were further classified into different formations. Kutty et al. (1987) assembled the previous work and subdivided the Maleri Group of King into four conformable formations based on the lithological and faunal distinctions viz. Yerrapalli, Bhimaram, Maleri and Dharmaram, in ascending order of succession. Dasgupta and Ghosh (2018) presented the updated stratigraphic classification of the Upper Gondwanas of the PG Basin, based on a number of studies (Jain et al. 1964, 1983; Kutty 1969, 1971; Sengupta 1970, 2003; Rudra 1982; Bandyopadhyay and Rudra 1985; Kutty et al. 1987, 2007; Kutty and Sengupta 1989; Dasgupta 1993; Ray and Bandyopadhyay 2003; Bandyopadhyay and Sengupta 2006; Bandyopadhyay et al. 2010; Novas et al. 2011; Dasgupta et al. 2017). The Yerrapalli Formation (400–600 m thick) is dominantly composed of reddish brown to violet mudstones having poorly developed gypsum crystals, subordinate calcareous quartzose sandstones and smaller lenticular bodies made up of peloidal carbonate grains. The Bhimaram Formation (~400 m thick) is dominated by coarse, pebbly, clay gall bearing, yellowish brown to whitish feldspathic sandstones intercalated with a minor proportion of red mudstones. The Maleri Formation (~300–500 m thick) is a part of the Triassic redbed succession of the PG Basin. This formation is essentially composed of stratified red mudrocks, fine-grained white sandstones along with subordinate carbonate grainstones and marls (Dasgupta et al. 2017; Dasgupta and Ghosh 2018). The Dharmaram Formation (400–600 m thick) has thick basal sandstone followed upwards by a series of alternations of arkosic sandstone and mudstone beds with subordinate carbonates. The Dharmaram Formation conformably grades up to the Kota Formation, which starts with coarse, pebbly sandstone grading upwards to white fine sandstone, red clays, calcareous shales and limestones (Kutty et al. 1987; Goswami et al. 2018). Towards the northwestern part of the basin, the Gangapur Formation overlies the Kota Formation. The Gangapur Formation is made up of coarse to very coarse ferruginous sandstone with pebble bands in its lower part, succeeded by sandstones and mudstones having concretions (Kutty et al. 1987). Planar and trough cross-bedded medium- to coarse-grained sandstone units show paleocurrent direction towards the north. Towards the eastern part of the basin, the Kota Formation is overlain by the Chikiala Formation consisting of coarse to very coarse ferruginous sandstones, subordinate red clays and calcareous


A
NE
SW
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C
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E
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H

◂**Fig. 2** Field photographs showing different lithologies of the Gondwana basins. **a** Large scale normal faulting observed in the sandstone outcrop (35° towards 040°) of the Kundaram Formation (PG Basin) near Annaram bridge over Godavari river. The sense of movement has been identified from the slickensides (inset) observed in the hanging wall block (box highlighted). The fault has thick (3–5 cm) shale gouge. **b** Lithology of the Chikiala Formation (PG Basin) showing ripple laminated very fine sandstones (40–50 cm thick) and greenish clay (30–40 cm thick), separated by calcareous sandy material (10–20 cm thick, marked by dashed white line). **c** Lithology of the Pachmarhi Formation (Satpura Basin) showing cross-bedded very coarse pebbly sandstone, near Dhupgarh. The paleocurrent direction is away from the observer. **d** Plan view of hardpan of calcic vertisol of the Bagra Formation (Satpura Basin). **e** Calcic paleosol profile having red mudstone as host rock of the Lameta Formation (Satpura Basin) near Ghughura falls. Greenish-grey patches are gley. **f** A carbonate profile with rhizocretions within mudrock (area marked in dashed white box) of the Tiki Formation (Rewa Basin), near Jora village. **g** Occurrence of gypsum crystals (arrow) scattered within red mudrock of the Tiki Formation. **h** Carbonate concretion found in the red mudrock of the Tiki Formation (hammer length = 38 cm)

sandstones (Kutty et al. 1987). New findings from Chikiala Formation reveal very fine sandstones and greenish clay separated by calcareous sandy material having crystal veins (Fig. 2b). Detailed sedimentology of upper Kota, Gangapur and Chikiala formations are yet to be done.

2.1.3 Fossil Content

The fossils within the Lower Gondwana formations are discussed in detail by Ray (1999). The Permian rocks of the PG Gondwana Basin was characterized by the *Glossopteris* flora, found in the Barakar Formation (Pascoe 1959; Robinson 1967). The Kundaram Formation of this basin yields the only Permian reptilian fauna in India, which constrains the upper age of the coal-bearing Damuda Group of the Damodar Gondwana Basin as Tartarian.

The Upper Gondwanas contain a number of vertebrate fossil (amphibians, reptiles etc.) bearing zones that are important for inter basinal correlation of the strata and for assigning age. A large number of fossils have been reported from the Triassic and Jurassic formations of the PG Basin by different workers (Kutty and Sengupta 1989; Bandyopadhyay et al. 2010). These fossils mainly occur in the red mudstones, and in very rare instances in the sandstones. Based on the faunal assemblages and dispositions of the litho-units, Yerrapalli, Bhimaram, Maleri and Dharmaram formations were assigned (Anisian) early Middle Triassic, late Middle Triassic (Ladinian), (Late Carnian–Early Norian) late Late Triassic, and late Late Triassic to early Early Jurassic ages, respectively (after Jain et al. 1964; Chatterjee 1967; Kutty 1969; Sengupta 1970; Anderson and Cruickshank 1978; Kutty and Sengupta 1989; Sarkar and Chaudhuri 1992; Ray and Bandyopadhyay 2003; Bandyopadhyay et al. 2010; Bandyopadhyay 2011). Yerrapalli Formation consists of numerous fossils of fishes, amphibians, reptiles and also trace fossils (Dasgupta 1993). Apparently, no faunal assemblages have been found in the Bhimaram Formation, apart from plant fossils and few fragments of vertebrate fossils. The Maleri Formation has an exceptionally rich vertebrate assemblage consisting of aquatic, semi-aquatic as well as terrestrial fossils. Numerous fossil vertebrates and invertebrates, and coprolites have been reported from the Maleri Formation (Jain 1983; Kutty et al. 1987, 2007; Kutty and Sengupta 1989; Bandyopadhyay and Sengupta 1999; Martin et al. 1999; Datta et al. 2004; Datta 2005; Datta and Ray 2006; Bandyopadhyay and Sengupta 2006; Nath and Yadagiri 2007; Bandyopadhyay 2011). Invertebrates are represented by unionids, while plant fossils are represented by *Dadoxylon* (Sohn and Chatterjee 1979). The Maleri vertebrate fauna is characterized by different species of fish, amphibian and reptile. The upper part of the Dharmaram Formation and the overlying lower part of the Kota Formation has been assigned an Early Jurassic age (Kutty et al. 1987; Mukhopadhyay et al. 2010; Bandyopadhyay 2011). An exceptionally rich fossil assemblage, consisting of non-marine aquatic, semi-aquatic as well as terrestrial vertebrates (fishes, reptiles, amphibians, etc.) along with invertebrates (unionids), plants and trace fossils has been reported from Dharmaram Formation (Pascoe 1959; Kutty 1971; Chatterjee and Roy Choudhury 1974; Sarkar and Chaudhuri 1992; Bandyopadhyay 2011). Very large (<15 feet) petrified wood, mainly tree trunks have been found in the Dharmaram Formation. Based on this faunal assemblage, a Hettangian age has been assigned for the upper part of the Dharmaram Formation (Bandyopadhyay and Sengupta 2006). The lower part of the Kota Formation yields fossils of sauropod dinosaurs, flying reptiles, turtles and other reptiles as well as fish, early mammals, ostracods, estherids, charophytes etc. (Kutty 1969; Yadagiri and Rao 1987; Jain 1973, 1974, 1983; Evans et al. 2002; Bandyopadhyay and Sengupta 2006; Bandyopadhyay et al. 2010; Goswami et al. 2018). Based on the faunal analysis, Sinemurian to Pliensbachian age has been assigned to the lower part of the Kota Formation. Systematic paleobotanical investigation suggests an Early to Middle Jurassic age for the Kota Formation (Chinnappa and Rajanikanth 2016a). The Gangapur Formation, overlying the Kota Formation, has been assigned Early Cretaceous age from its fossil assemblage, having abundant well-preserved leaves, macroflora and spore-pollens (Ramakrishna et al. 1985; Chinnappa and Rajanikanth 2016b). However, due to the lack of fossil content, the age of the overlying Chikiala Formation remains debatable.

2.2 Satpura Basin

2.2.1 Tectonics

The Satpura rift Basin, the westernmost Gondwana basin of peninsular India, is rhomb-shaped and elongated in ENE-WSW direction (~200 km long and ~60 km wide). The regional strike of this basin is NE-SW and the regional dip (~5°) is northerly (Chakraborty et al. 2003). Sub-vertical, ENE-WSW trending en-echelon faults, Son-Narmada South and Tapti North, with evidence of strike-slip movement, mark the longer sides of the Satpura Basin (Biswas 1999, 2003). This basin represents a pull-apart origin that developed above a releasing jog of a pre-existing transcurrent zone as a result of sinistral displacement (Chakraborty and Ghosh 2005). The Satpura Gondwana Basin is bounded by the Mesoproterozoic Vindhyan sediments to the north, Precambrian granitic gneiss to the south and late Cretaceous Deccan Traps towards the east and the west. A thin belt of Paleoproterozoic rocks of Bijawar and Mahakoshal groups are squeezed in between the Son-Narmada North Fault (SNNF) and Son-Narmada South Fault (SNSF). The Satpura Gondwana sediments were deposited in a mega half-graben (Veevers and Tewari 1995; Biswas 1999), which later got uplifted over the Pachmarhi plateau of Central Indian Tectonic Zone (CITZ), also referred to as the Satpura Mountain Belt in central India (Mohanty 2010; Singh et al. 2015). Sediment accumulation took place under different fault-controlled subsidence regimes, with intervening tectonically static periods. The subsidence rate varied across the basin, with the thickness increasing towards the north, resulting in an asymmetric basin fill (Chakraborty and Ghosh 2005). Many tholeiitic dyke intrusions of late Cretaceous Deccan flood basalt are exposed in and around the Satpura Basin, the majority of which are aligned along the ENE-WSW trend and represent the oldest intrusive phase. Some of the dykes are seen passing into sills (Bhattacharji et al. 1996; Sheth et al. 2009). The updated geological map is given in Ghosh et al. (2012).

2.2.2 Stratigraphy and Lithology

The Satpura Gondwana intracratonic basin preserves ~5 km thick Permain to Cretaceous siliciclastic sediments (Crookshank 1936) that unconformably overlies the Precambrian basement of schist, gneiss, granites, meta-sediments, mafic and acid volcanic rocks (Ghosh and Sarkar 2010). The Satpura Basin comprises a thick sequence of Lower and Upper Gondwana sediments. The gross thickness of the lower Gondwana rocks (lower Carboniferous to upper Permian) is reported to be around 3000 m and the upper Gondwana rocks (lower Triassic to upper Cretaceous) around 2000 m thick (Peters and Singh 2001; Ghosh et al. 2012). Geological studies including sedimentology, stratigraphy, and paleontology of the Satpura Basin has been carried out by various researchers (Casshyap et al. 1993; Veevers and Tewari 1995; Mukherjee and Sengupta 1998; Bandyopadhyay and Sengupta 1999; Nandi and Raha 1998; Maulik et al. 2000; Ghosh et al. 2004, 2012 Chakraborty and Ghosh 2005, 2008; Chakraborty and Sarkar 2005; Ghosh et al. 2006; Ghosh and Sarkar 2010; Bandyopadhyay 2011; Sengupta et al. 2016). The Satpura Gondwana succession has been classified into nine lithostratigraphic units that from oldest to youngest are the Talchir, Barakar, Motur, Bijori, Pachmarhi, Denwa, Bagra, Jabalpur and Lameta formations. Bijori and Pachmarhi formations share an unconformity, so does Denwa and Bagra formations.

Distinctive lithologies characterize each of the five formations comprising the Mesozoic succession of the Satpura Basin. The preliminary study of the Pachmarhi Formation (~900 m thick) shows multistoried bodies of very coarse pebbly sandstone (Fig. 2c) with minor red (with few calcic vertisols) to grey mudstone units. The detailed sedimentological work reveals that the Denwa Formation (~600 m thick) consists of red mudstone, heterolithic strata, fine to coarse sandstone, caliche profiles and intraformational calcirudite/calcarenite. The Bagra Formation (~400 m thick) is composed of gravelly conglomerate, pebbly sandstone, red mudstone with calcareous nodules with abundant calcic vertisols (Fig. 2d) (Ghosh and Sarkar 2010; Ghosh et al. 2012; Sengupta et al. 2016). The Bagra Formation is unconformably overlain by Jabalpur and Lameta formations (Ghosh et al. 2001; Prakash 2008). The Jabalpur Formation (~20 m thick as exposed) consists of coarse sandstone, white mudstone and thin stringers of coal (Dogra et al. 2010). The Lameta (~20–50 m thick as exposed) Formation consists of fine-grained calcareous sandstone, green sandstone, coaly shale, red mudstones, limestones, mottled nodular marl and calcic paleosol profiles (Fig. 2e) (Ghosh et al. 1995, 2001; Dogra et al. 2010; Bansal et al. 2018).

2.2.3 Fossil Content

Since no radiometric age dating has yet been carried out, fossil content was used to constrain the age of the Satpura Gondwana succession. Based on the available marine invertebrates, the Lower Gondwana succession has been designated an age from Late Carboniferous to Late Permian. The Upper Gondwana succession ranges in age from Early Triassic to Cretaceous (Ghosh et al. 2001, 2012; Ghosh and Sarkar 2010; Sengupta et al. 2016). The Upper Gondwana starts with the Pachmarhi Formation (Early Triassic) and consists of few fragmentary weathered amphibian skull bones along with the absence of *Glossopteris*-*Gangamopteris* flora (Bandyopadhyay and Sengupta 1999; Chakraborty and Sarkar 2005; Ghosh et al. 2012). The Denwa Formation (Middle Triassic-Anisian, Bandyopadhyay and Sengupta 1999) exhibits fossils of fishes, and vertebrate faunas of various types of amphibians, reptiles and herbivorous animals along with invertebrates-*Unionids* (Bandyopadhyay et al. 2002; Bandyopadhyay 2011; Sengupta et al. 2016). The age of the Bagra Formation is controversial. Previous workers considered this as Jurassic (Ghosh et al. 2001; Ray and Chakraborty 2002; Chakraborty and Sarkar 2005; Ghosh and Sarkar 2010; Mukhopadhyay et al. 2010; Ghosh et al. 2012). Based on the vertebrate fossil content, the Bagra Formation has been presently assigned as Cretaceous (Bandyopadhyay and Sengupta 2006; Bandyopadhyay 2011; Sengupta et al. 2016). From palynological studies, Jabalpur Formation and Lameta Formation are assigned to Early and Late Cretaceous (Maastrichtian), respectively (Dogra et al. 2010). The Jabalpur Formation includes plant fossils (Ghosh et al. 2001). The Lameta Formation exhibits semi-aquatic, aquatic communities and wood fossils represented by dinosaurs, fishes, crocodiles, gastropods, ostracods, charophytes, conifers, angiosperms (Mohabey et al. 1993; Khosla and Sahni 2000; Ghosh et al. 2003; Kar et al. 2004; Wilson and Mohabey 2006) and trace fossils (Saha et al. 2010) along with palynological evidence (Dogra et al. 2010).

2.3 *Rewa Basin—A Sub-basin of the Son-Mahanadi Basin*

2.3.1 Tectonics

The Son-Mahanadi Basin is a composite basin comprised of three sub-basins, namely the Rewa Basin to the north, the Hasdo-Arand Basin to the central position and the Mahanadi Basin to the south (Agarwal et al. 1993). All these three sub-basins are separated by three ridges starting from North Malwa ridge, followed southward by Manendragarh-Pratapur ridge, and then Naughata ridge (Chakraborty et al. 2003). The southwestern margin is concealed by the thick cover of Deccan Traps. The Rewa Basin is rhomb-shaped and is relatively long in the ENE-WSW direction (400 × 150 km, Chakraborty et al. 2003). Bouguer anomaly also conforms to the shape of the basin. The Rewa Basin was formed due to strike-slip motion, and the basin profile indicates fault-controlled subsidence. The overall attitude of the basin-fill strata is subhorizontal (~4–5°) with a northward dip (Chakraborty et al. 2003; Mukherjee et al. 2012). The updated geological map is given in Mukherjee and Ray (2012).

2.3.2 Stratigraphy and Lithology

The geological study of the Rewa Gondwana Basin was initiated by Hughes (1881) and subsequently followed by a number of workers such as Cotter (1917), Fox (1931, 1934), Rao and Shukla (1954), Dutta and Ghosh (1972, 1993), Raja Rao (1983), Mitra (1993), Tarafdar et al. (1993), Dutta (2002) and Shah (2004). The Gondwana sediments of the Rewa Basin is subdivided into lower and upper divisions based on the presence of *Glossopteris* and *Ptilophyllum* flora, respectively (Pascoe 1975). The sediments of the Rewa Basin comprise a basal Talchir Formation, followed by the coal-bearing Barakar Formation, and then the Mesozoic formations (Shah 2004). The Mesozoic formations start with the Pali Formation (~1000 m), which is overlain by the Parsora Formation (~400 m) in the southwestern part. Whereas it laterally grades into the sand-dominant Karki Formation (~300 m) in the north-eastern part (Mukherjee et al. 2012). These units are overlain by the mud-dominated Tiki Formation (~400 m). This, in turn, is overlain unconformably by the Hartala Formation (Shah 2004), which is characterized by typical Upper Gondwana flora of Jurassic affinity (Sahni and Rao 1956). But, according to Mukherjee et al. (2012), no lithological distinction was found between Parsora and Hartala formations. Hence the Parsora Formation constitutes the youngest member of the Rewa Gondwana succession. The Pali Formation is composed of pebbly to coarse-grained micaceous sandstone, medium- to fine-grained sandstone, moderate red, greyish green and greyish yellow coloured mudstone having incipient development of paleosol profile (Dasgupta 2009). The Karki Formation is characterized by multistoried, multilateral sheet-like beds composed of pebbly to very coarse quartzo-feldspathic sandstone. The Tiki Formation comprises subhorizontal to horizontal beds of red mudrock with paleosol profiles. Mudrocks exhibit gypsum