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D. M. Banerjee
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Tectonics of the Indian Subcontinent

The Society of Earth Scientists
2008

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ISSN 2194-9204 ISSN 2194-9212 (electronic)
Society of Earth Scientists Series
ISBN 978-3-030-42844-0 ISBN 978-3-030-42845-7 (eBook)
https://doi.org/10.1007/978-3-030-42845-7

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Series Editor Foreword

The Indian subcontinent has been a unique landmass in the history of the evolution of Earth carrying oldest to youngest rock records and imprints of various tectonic episodes. Unraveling the geological mystery has been the continuous endeavor of geoscientists. Active Himalayan chain, peninsular cratonic shield, sedimentary basins of almost all ages, Precambrian and Phanerozoic plate-tectonic movements and associated tectonism offered natural laboratory to carry out geological studies. As such extensive research has been attempted in the recent past. The compilation and interpretation of existing data and opening new vista have been the ultimate objective of any book. The volume on the tectonics of the Indian subcontinent, thus, is a praiseworthy attempt by a group of renowned geoscientists. I believe that the book will act as a classic compilation for both students and researchers equally. I express my personal gratitude to all the authors for their exemplary contribution to the field of geology and tectonics of India.

The mega-event of 36th International Geological Congress 2020 in India opened a new chapter on the geology of India. On such an occasion, the Society of Earth Scientists Series by Springer decided to bring out 36th IGC Commemorative Volumes on various recent geological and geophysical studies of India. As such, veteran geoscientists were requested to prepare comprehensive accounts as monographs or edited volumes. I am personally thankful to all the editors and authors for the timely submission of high-quality manuscripts for inviting the interest of the global community of geoscientists.

Lucknow, India

Satish C. Tripathi
Series Editor

Preface

It is now a common knowledge that the Archean Eon (4.0–2.5 Ga) witnessed the preservation of thick piles of rocks, following the early cooling and emergence of the Earth's crust during the Hadean times. Several workers have postulated that water released during mantle outgassing and its accumulation in liquid form within the shallow depressions on the early Archean mafic crust is one of the key differentiators in the unique trajectory of crustal evolution on the Earth and the other planets (Taylor and McLennan 2009). Records of Earth's primitive atmosphere possibly seem to have been successfully documented in the Eoarchean records, known only from Australia and India to date. Different forms of cyanobacteria are identified in the 3.75–3.5 Ga Paleoarchean rocks. Magmatism, sedimentation in the shallow marine and terrestrial basins, dominated the geological scenario throughout the Archean when magmatic greenstone belts developed along with the emergence of sizeable continental crust. As rightly pointed out by Eriksson and Mazumdar (2019) "—the cratonic nuclei (proto-cratons) in some parts of the globe had attained a measure of geodynamic stability in the Meso- and Neoarchean; early supercratons heralded their much larger successor supercontinents which emerged during the succeeding Proterozoic Eon."

The progressive growth of continental crust led to changes in the style of tectonics gradually across the Archean–Proterozoic transition, from vertical/lid tectonics to Phanerozoic plate-tectonic style (Condie, 2018). Many geodynamic and metallogenic events in the Earth's history have close linkage with the transition time between the Archean and Proterozoic. Widespread oxidation of the paleo-ocean and -atmosphere represents the Great Oxidation Event followed by worldwide (?) glaciation as evident from Archean–Proterozoic glacial diamictites in many parts of the world including some terrains of central India. Climatic changes in cratons led to the creation of a highly modified hydrosphere which allowed the proliferation of biota and precipitation of iron in large basins across the continents. Although the Archean–Proterozoic boundary is chronologically placed at 2.5 Ga, this time plane is not sacrosanct in terms of tectonic styles, which varies in different continents, depending upon the evolutionary traits shown by the rocks across this boundary. These changes in tectonic regime and style appear reflected in the Archean and Proterozoic rock records of Peninsular India. This $\sim$2.45–2.3 Ga period is considered as a time of global magmatic shutdown or slowdown with concomitant influences on the supracrustal record. It is, however, necessary to realize that in spite of such vast differences in tectonics, climate and basin configurations, both the Archean and Proterozoic basins show significant similarities with the Phanerozoic basins, barring the prominent influence of biota in the latter. Hence, Phanerozoic analogs can be discerned all over the Precambrian terrains of the Indian subcontinent.

The geological evolution of the Indian Peninsula during the Phanerozoic is one long hiatus (punctuated by relatively localized events), indicating that this crustal block remained an emergent continental block throughout the last 600+ million years. The exceptions are the events resulting from the breakup of Gondwana, which left behind coal-rich intracontinental Gondwana basins, including the separation from the Australia–Antarctica blocks. This event is followed by rifting of this block from Madagascar and then other smaller microcontinents on the west and its passage over hotspots (Kerguelan and later Marion–Reunion), currently located in the Indian Ocean that led to the development of one of the largest flood basalt provinces in the world during the Cretaceous–Paleogene transition. Only the northern edge of the Indian Peninsular was tectonically active during the Phanerozoic with a series of basin forming, collisional events that remain preserved in the Himalayan domain. The northward flight of the Indian Plate and its underthrusting/subduction beneath Asia in the last 100 million years has resulted in dramatic changes, marked by the rise of the spectacular Himalayan mountains and the wide frontal alluvial belt. This has affected the climatic systems of the northern Indian Ocean during the Quaternary.

Significant advancements have been made in the field of paleobiology, sedimentology, stratigraphy, crust–mantle interactions, paleomagnetism, and geodynamics in recent years. These new data supported by precise radiometric dates have enriched geological literature on the Indian subcontinent in the past two decades. Several books have been published recently which focus on specific tectonics and/or stratigraphy of this region. Excellent compilation by Ramakrishnan and Vaidyanadhan (2008) and Valdiya (2016) dealt with all aspects of the geology of India, including physiography, stratigraphy, tectonics, mineral deposits, and evolution of life. Sharma (2009) and Roy and Purohit (2018) focused on the Archean cratons and Proterozoic mobile belts. Yet, much of the recent data has not yet found a place in a single compilation.

Our book has made an attempt to fill this gap for researchers and students. We have followed the philosophy which believes that the behavior of the parent affects its children all through their existence. Here, we consider the Archean Eon, which resides in the cratons as the geological parent, gave rise to the mobile belts in the subsequent era while other Proterozoic and younger fold belts formed in a well-defined sequence determined by the movement of the tectonic plates. The geodynamic processes led to the creation of specific terrains displaying regional as well as local characters. Final configuration and vulnerability of these terrains to the dynamic Earth processes like effusion/intrusion of magma, uplift, burial, weathering, erosion, transportation, and sedimentation remain solely controlled by the tectonics. Stratigraphy, the backbone of all geological studies, is also exclusively tectonic-dependent; hence, this book on Tectonics of the Indian subcontinent has substantial stratigraphy inputs.

We have divided the book into chapters beginning with the description of the oldest parent, the Archean cratonic terrains of the Aravalli, Bundelkhand, Meghalaya, Bastar, Singhbhum, and Dharwar. We have mentioned about a Marwar craton, suspected to exist west of the Aravalli craton. This is followed by the chapter on the immediate offspring of deformed, metasedimentary belt associated with the effusive and intrusive igneous rocks. These represent the mobile belts, exclusively confined to the Proterozoic Era and inferred to have deposited on the cratonic Archean basement. Mobile belts of the Aravalli–Delhi, Satpura–Sausar (Central Indian Tectonic Zone), Singhbhum, Eastern Ghats, and Pandyan are the major constituents which are spread all over the Peninsular India. Each one of these mobile belts has been treated as independent as well as interlinked entities with reference to tectonism and stratigraphy. These Proterozoic mobile belts as well as the cratons supported a large number of intracratonic basins comprising undisturbed to mildly disturbing sediments with occasional volcanic episodes preserved as dikes, sills, and ash beds. Some of the prominent basins are the Marwar, Vindhyan, Bijawar, Gwalior, Chhattisgarh, Cuddapah, etc., along with a number of smaller basins resting over the mobile belts or directly on the Archean basement. The rocks range from Stratherian to Ediacaran periods. In some of these basins, Fortunian age trace fossils have been recorded. The Proterozoic basin of Pranhita-Godavari valley is a rift-related basin and served as the depository of the Gondwana Paleo-Mesozoic coal, which was deposited in many other half-grabens of Central India.

The Himalayan Orogen with extensive mobile belt characters of folding, faulting, and thrusting has been treated as an exclusive segment and is primarily covered by the Proterozoic rocks with sporadic Phanerozoic outliers. In the continuity of the Himalayan Orogen, the Indus–Ganga–Brahmaputra foredeep sediments are affected by deep-seated tectonism which controlled the distribution of Neogene sediments within the linear E-W trending belt. The delta front of this basin stretches into the Bangladesh territory.

The Deccan Volcanic Province occupying vast plateaux has a long history and has been the focus of the attention of volcanologists, petrologists, and paleontologists given its temporal proximity to the terminal Cretaceous mass extinctions across the world. A description of this domain has been included highlighting areas that require attention in future studies to unravel the controversies associated with it. The closely-linked and greatly influenced by the Deccan volcanism, the Western Ghats (Sahyadri Ranges), gave the basic shape to the Indian Peninsula and therefore dealt in an independent Chapter.

Geology, stratigraphy, and subsurface tectonics of predominantly alluvial Bangladesh have been included as an independent chapter. In contrast to alluvial Bangladesh, Sri Lanka geology and tectonics are primarily related to the high-grade metamorphics of Archean–Proterozoic ages. Nepal and Bhutan have been included under the Himalaya chapter. The two other countries of the Indian subcontinent, the Myanmar and the Pakistan, could not be covered due to logistic constraints.

Our journey for writing this book on Tectonics of the Indian subcontinent began with a chance interaction of A. K. Jain with Satish C. Tripathi who reposed faith to take up the task of completing a book under the Society of Earth Scientists Series for the Springer. In turn, Jain invited D. M. Banerjee to join him in this endeavor. Midway through this journey, A. K. Jain and D. M. Banerjee decided to invite Vivek S. Kale to be the third author for this book. All three of us express our gratitude to Satish C. Tripathi and thank him profusely for this invitation. In the same go, we wish to thank M/s. Springer for publishing this book linking it with the 36th International Geological Congress in Delhi and Ms. Monica Janet Michael for carrying out all the necessary correction at various stages.

In the course of writing, we consulted a large number of books, papers, and reports and used valuable information and data contained in them. We are grateful to all the unnamed authors and publishers whose data sets were used in this book. We thank all our colleagues in the workplace and in other institutions for sincere advice and giving permission to use their published and unpublished data for improving the scientific content of the book, including the original drawings. M. Jayananda, Jayanta Pati, Naresh Pant, Maibam Bidyananda, J. P. Srivastava, and several anonymous knowledgeable went through different chapters of this book and offered valuable suggestions for improvement.

A. K. Jain would like to thank Sandeep Singh for his contributions to the Himalayan Tectonics in the field, and otherwise over the years, Rahul Dixit and Gargi Deshmukh who gave him technical assistance in formatting the text, figures, tables, and indexing as and when required. D. M. Banerjee would like to thank Anupam Chattopadhaya, Partha Chakravarty, Naresh Pant, and Fareduddin for scientific discussion on many aspects of Proterozoic geology. D. M. Banerjee wants to thank Aditi from DU for some CorelDRAW drawing, his granddaughter Kritika for assisting in desktop-related problems which he could not tackle and to Aniruddha and Roma for physical, logistic, and moral support during late-night sittings on the home Desktop. D. M. Banerjee remains indebted to his wife Late Anjali for her moral and physical support all through his professional life. A. K. Jain is grateful and highly obliged to his wife Kamlesh for encouraging him to achieve the target but patiently suffering through long lonely hours which was imposed on her during the last many months. He thanks his sons Manish and Ankur in the USA for a very academic house environment where a considerable part of this book was completed.

Vivek wishes to place on record his deep gratitude to his teacher Prof. V. V. Peshwa for his teaching and guidance and thanks to Kanchan Pande, Makarand Bodas, Abhay Mudholkar, Anand Kale, Himanshu Kulkarni, Raymond Duraiswami, Gauri Dole, Shilpa Patil Pillai, Shreyas Mangave, Ninad Bondre, and Vinit Phadnis for collaborating research on the Deccan Traps and related geology.

Both A. K. Jain and D. M. Banerjee thank the Indian National Science Academy for awarding the Honorary Scientist positions, during the tenure of which this book was written.

Roorkee, India	A. K. Jain
Delhi, India	D. M. Banerjee
Pune, India	Vivek S. Kale

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Contents

About the Authors

Prof. A. K. Jain obtained his Ph.D. in Geology from the erstwhile University of Roorkee and now the IIT Roorkee. After a brief career as a Scientist at the Wadia Institute of Himalayan Geology, Delhi (now at Dehradun), his interest in teaching brought him to the University of Roorkee in 1974 where he taught structural geology. He retired from the IIT Roorkee in 2007 as Professor and remained at the Institute as Emeritus Fellow till 2011.

He was a Fellow, Alexander von Humboldt Foundation (1979–1981) at the University of Karlsruhe, Germany, where he carried out postdoctoral research on Rift Tectonics of the Upper Rhine Graben. He was a Visiting Young Scientist at Bedford College, London, in 1979 under UGC-British Council Exchange Program, the Visiting Scientist at the Lund University, Sweden (1991), and a Senior JSPS Fellow (2004) at the Hokkaido University, Japan. He was a member of many Selection Committees and Project Advisory Committees of Earth Science Division of the Department of Science and Technology (DST), Government of India, New Delhi, besides Chairman of some of them. He is a Fellow of the Indian National Science Academy (FNA), New Delhi, and is currently active as the INSA Honorary Scientist at the CSIR-Central Building Research Institute, Roorkee.

He has written and edited five books on the Himalayan Geology and authored more than 120 research publications. He has supervised 15 Ph.D. students besides many for their dissertations. Some of his students are currently occupying high positions in teaching and government. His main area of research interest remained the

Himalayan Tectonics since the beginning. The book on the *An Introduction to Structural Geology*, published by the Geological Society of India, Bangalore, is an outcome of his teaching and research in the subject.

Prof. D. M. Banerjee obtained his Ph.D. Degree in 1967 from the University of Lucknow on a thesis on Himalayan Geology. He taught for a year in Dehradun and then spent nearly 2 years in the Geological Survey of India working on geohydrology and Precambrian geology. He joined the University of Delhi in 1970 and retired as Professor in 2007. He taught sedimentology, sediment geochemistry, and Precambrian stratigraphy.

He was a Visiting Lecturer in 1976 under the UGC-British Council Young Scientist Scheme at the University of St. Andrews, Scotland, and spent part of this tenure at the Universities of Glasgow, Reading, Keel, and Institute of Geological Sciences (now British Geological Survey). He was Fellow of the Alexander von Humboldt Foundation between 1982 and 1984 at the Max Planck Institute für Chemie, Mainz, West Germany, and had several short stints as AvH Visiting Professor at the Universities of Munster, Munich, and TU Berlin. In 1997, he initiated an IGCP-156 program on Phosphorite, served as its National Convener, and guided the IGCP-386 as the Global Co-Leader. He conducted a DFG funded long-term research program on Phosphorite at the MPI, Germany, and British Council-UGC funded program on groundwater Arsenic at the University College London, UK. He was a Visiting Professor at the University of Shizuoka under the INSA-JSPS exchange program. He Chaired the Department at the Delhi University and mentored many Ph.D. and M.Sc. level students between 1970 and 2007. He served as an expert member in the Scientific Advisory Committees of scientific departments of the Government of India and the University Grants Commission. He co-chaired the UGC committee for the revision of the geology syllabus in Indian universities. As Chairman of the National Committee for IUGS, INQUA, and ILP, he led the Indian delegation to the 34th International Geological Congress where India won the bid to hold the Congress in 2020. He was elected Fellow of the Indian National Science Academy (INSA), New Delhi, in 1999, INSA Senior Scientist in 2007, and Honorary Scientist in 2012 and will join as Emeritus Scientist in 2020.

He edited and co-edited six books on subjects related to phosphorite, stromatolite, sedimentology, and Earth Sciences. He served as a scientific reviewer for many Indian and International journals and served in International selection panels. Presently, he concentrates on themes concerning geoethics and geoheritage conservation.

Prof. Vivek S. Kale is a former Reader of Geology at the University of Pune and a former Adjunct Professor of Earth Sciences at the Indian Institute of Technology, Mumbai, with more than 30 years of teaching experience. He, currently, is the Managing Trustee at the Advance Center for Water Resources Development and Management, Pune (ACWADAM) and serves as the Head of Geospatial at Kalyani Global Engineering Private Limited. He is a Member/Fellow of Geological Society of India, Geological Society of America, Indian Geophysical Union, and Indian Society of Remote Sensing.

He specializes in tectonics, geomorphology and has extensively worked on the Purana Basins and Deccan Traps of India. He has recently authored the book on *Processes, Products, and Cycles of Tectonic Geomorphology* focusing on the process of landscape evolution, linking modified Davisian landscape, and Wilson tectonic cycles, sustainable land-use planning, and hazard mitigation.

Chapter 1
Tectonics of the Indian Subcontinent: An Introduction

1.1 Introduction

Geology and Tectonics of the Indian Sub-continent constitute a significant component of the Indian Plate straddling the equator as a part of the Gondwanaland that broke into fragments at ~100 Ma and started moving northwards. Once fused with adjacent Australia to form a single Indo-Australian Plate, recent studies suggest that India and Australia have been separate plates for at least 3 million years and likely longer. The Indian Plate includes most of South Asia—the Indian Sub-continent—and a portion of the basin under the Indian Ocean, parts of Tibet (South China) and western Indonesia, and extending up to but not including Ladakh, Kohistan, and Baluchistan (Fig. 1.1). Indus-Tsangpo Suture Zone marks the boundary of this plate with the northern Asian Plate. The plate has a convergent margin along the Himalaya in the north, transform margins in the west and the east, and the oceanic ridge in the Indian Ocean.

In this book, we have defined the Indian Sub-continent as the southern part of Asia comprising India, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka, and Myanmar. Tibet, once considered a part of this sub-continent, is linked to this landmass before Permian time. Although Myanmar, traditionally linked to the Indian Sub-continent, has many tectonic commonalities with the terrains of Thailand and Malaysia. From the geological point of view, all these countries share many standard geological features that transgress political boundaries. Countries surrounding the main Indian landmass invariably share the same tectonic and stratigraphic elements. In other words, the evolutionary history of this south Asian geographic segment is common, represented today by trans-country mountain ranges, rivers, coastline, and desert.

Contemporary workers have identified several physiographic/geological terrains, which display distinct lithological assemblages, specific orders of superposition, characteristic geomorphology, and tectonic history. We have classified these terrains confined by the Himalayan orogen, Trans-Himalaya, and the Karakoram in the north,

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A. K. Jain et al., *Tectonics of the Indian Subcontinent*, Society of Earth Scientists Series, https://doi.org/10.1007/978-3-030-42845-7_1

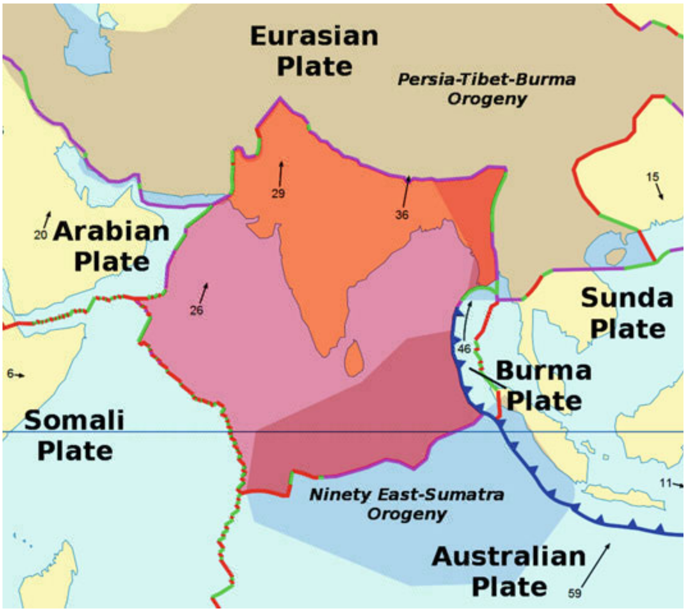

Fig. 1.1 The Indian Plate and its configuration. *Source* Tectonic plates boundaries detailed-fr.svg created by Sting under CC-BY-SA. File: Indian Plate map-fr.png

Kirthar and Sulaiman ranges in the northwest and west, Indo-Myanmar Ranges including Patkai, Naga, Arakan Yoma Mountains in the east extending into the Gulf of Thailand through the Bay of Bengal and the Arabian Sea in west and the Indian Ocean embracing it from the south.

Traditionally, the physiographic characteristics of the Indian landmass encompass the following (Fig. 1.2):

(i) Peninsular India with uplands and seacoasts,
(ii) The Himalayan Range including those in Pakistan and Myanmar, and
(iii) The Indus–Ganga–Brahmaputra Plain sandwiched between the two.

1.2 Peninsular India

1.2.1 Mountains and Plateaus

The NE–SW-trending Aravalli Range with Archean and Proterozoic rocks extends from Palanpur in Gujarat to Delhi and beyond subsurface up to Haridwar in the Gangetic alluvial plain. Granites extensively intrude these Precambrian rocks. The Aravalli range forms the water divide between the rivers of the Ganga and Indus

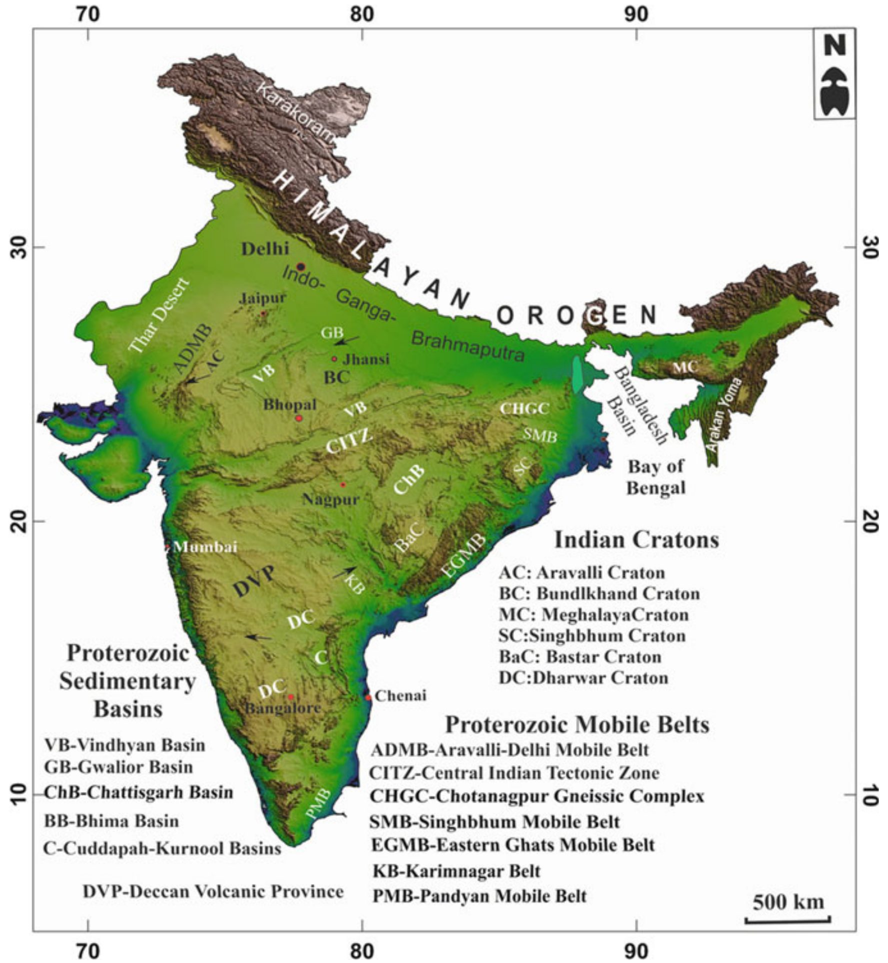

Fig. 1.2 DEM of the Indian sub-continent with major geological and tectonic units. Basic map courtesy Ajay Manglik (NGRI Hyderabad)

drainage systems. The Aravalli Range bends southeastwards to join the ENE–WSW-trending *Satpura Range*. Faulting along the Narmada valley disconnected the two mountain ranges. The Satpura Ranges extend ENE from southern Gujarat to central India and beyond. In the east, it embraces the *Rajmahal Hill* and *Chotanagpur terrain*. The *Shillong Plateau or* the *Meghalaya massif* borders Bangladesh and consists of the Garo Hills, the Khasi–Jaintia Hills and the Mikir Hills. The Shillong massif acted as a pivot for deflecting the Brahmaputra River westwards to skirt around the upland before joining the Ganga in Bangladesh.

In the central part of the Peninsula, the Satpura Range divides the landmass into the northern plateaus of Malwa, Bundelkhand, and Vindhyachal; the southern part comprises the Deccan, Mysore and Telangana plateaus. *The Deccan lavas also cover the Malwa Plateau*. *The Bundelkhand Upland with* Late Archean gneisses and granites occur in the deeply dissected ravines of Chambal River. The Kaimur and Bhainer Plateaus with steep escarpments occur in the *Vindhyan Range.* A large tract *s*outh of the Satpura Ranges and east of the Sahyadri is known as the *Deccan Plateau.* The upper Mesozoic lavas formed a flat terraced landscape with extensive bauxite and laterite cappings. The *Mysore Plateau, in the south,* made up of highly metamorphosed Archaean gneisses and granites form isolated hillocks of the Bababudan, the *Chitradurga Range* and the *Kolar Range* (Fig. 1.3).

From the Tapti Valley in the north to Kanyakumari in the south, the rugged N–S range is the *Sahyadri Range.* The upper Mesozoic Deccan basalt forms the *Northern Sahyadri*, the Archaean gneisses and high-grade metamorphic rocks that occur in the *Central Sahyadri* and late Proterozoic charnockites and khondalites form *Southern Sahyadri.* The NNW–SSE-trending fractures and faults make the Sahyadri Range a horst mountain. Its west-facing steep to near-vertical escarpments is known as the *Western Ghats*. East-flowing Godavari, Krishna, Tungabhadra and Kaveri rivers originate in the Western Ghats while some small rivers flow to the west. Between the towering Nilgiri massif and the Annamalai Range is the 25–30 km wide *Palghat Gap.*

Disconnected *c*harnockitic *Shevaroy Hills, Eastern Hills,* and highly tectonized Proterozoic *Nallamalai Hills constitute the East Coast.*

Several ancient Archean cratons constitute Peninsular India, each of these cratons acting as the basement for the deposition of the Proterozoic sediments which either ended up as variably metamorphosed and deformed mobile belts or remained as undisturbed intracratonic basins (Fig. 1.2). The entire Peninsular terrain suffered multiple orogenic cycles followed by sedimentation, erosion and weathering cycles all through its geological history. Mountains like Nilgiri–Aravalli, Sahyadri range, hills like Pachmarhi, plateaus like Deccan and Rajmahal, intra-hills plains, river basins fill, delta plains like Bengal–Mahanadi–Krishna–Godavari–Kaveri deltas, Western and the Eastern Ghats, coastal low lands like Sundarbans and manifestations of ancient tectonic sutures reflect the physiography of this entire segment. This terrain also supports freshwater riverine and lacustrine deposits which formed in the rifted basins in the central part of the Peninsula. The Gondwana Basin formed in these basins created during the Paleozoic–Mesozoic tectonics. This region is covered partially by late Mesozoic volcanic lava which has carved out distinct physiographic features dotted by pop-up Archean and Proterozoic inliers. In the northern part of the Peninsula, some of the Proterozoic rocks occur at considerable depth under the thick alluvial fills of the Ganga–Jamuna Plains and possibly extended much to the north and got mixed up with the rocks which formed the present-day Himalaya.

The late Paleozoic–early Mesozoic tectonics, which caused the formation of horsts and grabens in the central part of the Indian shield, got accelerated due to further northward drift of this rigid mass. In the process, some remnant upper Mesozoic basins were pushed northward and got buried in the alluvial plains. In the southern end of east-central India, bordering the alluvium of the Ganga Basin, the Damodar River valleys acted as the repository of a large quantity of riverine sediments. Likewise,

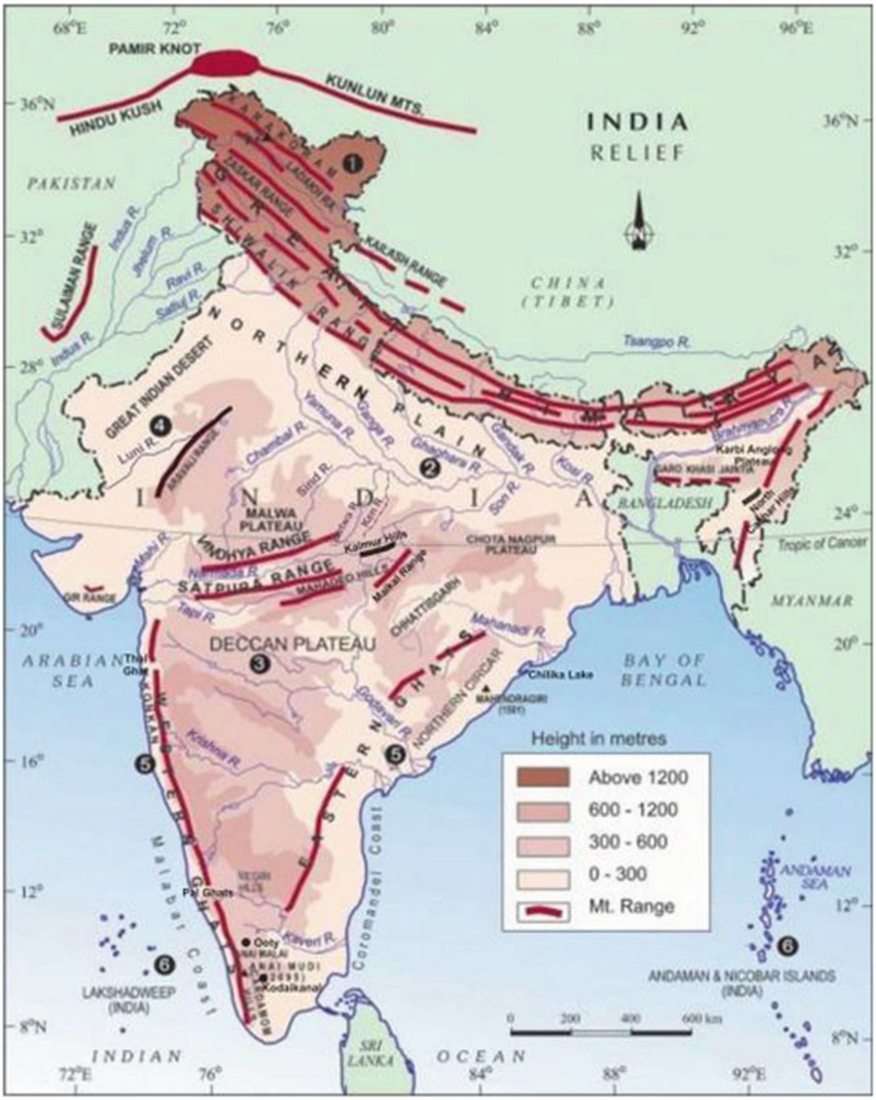

Fig. 1.3 Physiography of the Indian sub-continent showing major mountains, plateaus and basins

Mahanadi, Son, Pranhita and Godavari rivers carved out many linear horsts and grabens, trending E–W to NNW–SSE. These basins allowed the deposition of an exceptional thickness of fluvial sediments and preserved significant organic matter which turned into coal. These events began in late Permian time. Glacial deposits along with occasional intermixed marine sediments occur in some sectors which mark the waning phase of sedimentation in these basins. At the beginning of Permian, the glaciated Gondwanaland started sagging that allowed the oceanic waters to enter the heart of the continental landmass. This upper Paleozoic marine incursion is distributed along the Umaria–Manedragarh belt in central India and even extend up to Meghalaya in the east.

During the Upper Cretaceous, as a result of large-scale volcanic eruptions and outpouring of mobile lava, mafic volcanic rocks covered a large part of the Indian shield. These flat-topped plateau basalts formed by the volcanic eruption which started in Cretaceous time, around 69 Ma continued erupting till 61 Ma. These rocks identified as the *Deccan Traps* created by pulsating volcanic activities and allowed preservation of fossil-bearing sedimentary rocks during the quiescent period. These are Intertrappean and Infratrappean beds. The Deccan Traps are distributed all over the Western Ghats including the Konkan Coast. Kachchh–Saurashtra, Malwa Plateau, Rajmahal Hills and Sylhet Plateau also expose similar volcanic rock assemblages. Associated features like dyke swarms seen along the Konkan coast, Narmada and Tapti River valleys acted as conduits for outpouring lavas to spread over an extensive area. Along numerous lakes and swamps which came up due to damming of flowing rivers, supported a variety of plants and animals including giant reptiles like dinosaurs.

1.2.2 Coastal Plains

The Indian Sub-continent has more than 6000 km long coastline between the Indus delta to the southern tip of the Peninsula, the Bengal delta, along the Arakan coast, to the Irrawaddy delta (Fig. 1.4). Sri Lanka has a broad fringe of coastal plains all around. The *Makran Coast*, near the Indus deltaic plain, form an arcuate zone of older tidal-flat deposits. East-southeast of the Indus deltaic plain is the *Rann of Kachchh*, a salty marshy tidal flat.

The *West Coast* is mainly a *coast of submergence represented by* cliff faces and near-shore islands, estuaries, and backwaters. The coastal plain of Gujarat is the prolongation of the alluvial plains of the Sabarmati and the Mahi rivers. The *Gujarat Coast with* strand lines 8–10 m above the present sea level mark the northern end of the West Coast. A narrow strip of the *Konkan Coast* is a rocky shore of cliffs, bays, coves with small mudflats and small beaches.

The East Coast is a *coast of emergence*, characterized by well-defined beaches, dunes and sand spits, and many lagoonal lakes associated with backwater swamps. Pulicat Lake and the Chilka Lake are large coastal lakes on the eastern coast. A product of the combined contributions of the Ganga and the Brahmaputra, the Ganga–Brahmaputra–Meghna Delta, is called the *Sundarban Delta* which forms part of the coastal plain, creating the head of the Bengal Basin.

Fluvial Upper Jurassic to Quaternary sedimentary rock successions dots the Indian coast from west to south. These are pericratonic basins that formed in response to faulting along the coastal belt accompanied by intermittent sagging of the basin floor. The Middle Jurassic sediments in Kachchh and the Upper Jurassic strata in the Coromandal Belt are well preserved. Marine transgression also affected parts

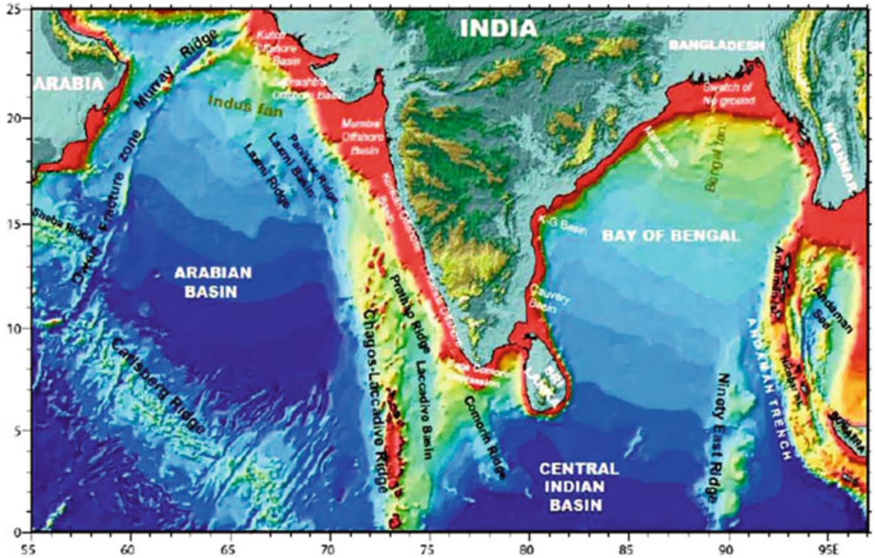

Fig. 1.4 Morphology off the littoral regions of India. Rifted passive margin controls east coast morphology whereas the west coast is marked by intense volcanism near the K–T boundary. After Fainstein et al. (2019)

of Bangladesh, southern Meghalaya and Western Rajasthan at different times. A narrow strip of marine bed in the Narmada river valley received sediments to form the Mesozoic Bagh Beds. The upper parts of these sedimentary piles are represented by Paleogene and Neogene sediments, which cover larger areas and form the continental shelves and continental slopes in eastern and western sea coasts.

1.2.3 Himalaya

The *Himalaya–Karakoram–Arakan* ranges formed as a result of the Indian and Asian Plate convergence and pushing up the mobile sedimentary fills of the Paleozoic Tethys Ocean with Peninsular rocks as the seafloor. The Himalayan mountains grew in height through multiple spasmodic episodes, and each spasm left its signature in the form of characteristic sedimentation, deformation, metamorphism patterns, and metallogeny. The Early Cenozoic was the period when docking and collision/subduction of the two major plates started leading to the initiation of the Himalayan tectonic domain. Extensive folding, large-scale thrusting, inversion of strata and subsequent erosion and degradation mark the history of this mountain chain. All these activities were repeatedly activated by seismic tremors that dominated the tectonic scenarios all through its history since birth from an oceanic cradle.

Beyond the Tethyan Himalayan Belt and across the *Indus* and *Tsangpo valleys,* a vast plateau region belongs to Tibet which is part of a different Asian landmass. This peneplaned uplifted plateau of 90–45 Ma old granites and granodiorites along our intermixed with 60–80 Ma old volcanic rocks.

The NW–SE to E–W trending Himalayan range show bending of strata on a very large-scale in western as well as eastern ends. On the northwestern end in the Kashmir region, the entire mountain chain shows abrupt bending of all the strata making an acute angle to the south. Even the structural features like faults and folds show a sharp change in their trend. This zone is called the *western syntaxis* around Nanga Parbat. The southerly bend of the Himalayan Range gradually splays out to the west as Sulaiman and Kirthar Ranges. In contrast, the *eastern syntaxis* developed at the east end of the Himalayan chain beyond the Arunachal Pradesh; both the syntaxes control the present-day U-shape bending and deep gorge of the Indus and Tsangpo Rivers, respectively.

In the east, the NW–SE trending Lohit–Mishmi Ranges in Arunachal Himalaya meets the NNE–SSW trending Patkai–Naga and Arakan–Yoma Ranges which undergo clockwise rotation, originated through an altogether different mechanism. These ranges extend into Myanmar, embracing the Indo–Myanmar Ranges along the coast with a westward bulge, a depressed Myanmar Central Belt region and the uplifted Shan Plateau in the east. With the opening of the Andaman Sea along the ridge, the system defines the Burmese microplate.

West of the Indus River in northern Pakistan lies the N–S trending ranges of Kohistan, Swat, and Dir with very high mountain peaks and steep slope faces. The Pir Panjal Range of Kashmir, after the syntaxial bend, is the *Hazara Ranges* trending NE–SW and comprising a series of hills. The Hazara belt of Pakistan is comparable to the Lesser Himalaya terrain in India. The Attock–Cherat Range and the Khyber Pass Range along with *Peshawar Plain* of Northwest Frontier Province are other mountainous terrains in Pakistan. South of the Hazara Ranges highly dissected *Kohat–Potwar Plateau* has the Salt Range on its southern margin. The N–S-oriented arcuate *Sulaiman Range* forms the eastern part of Balochistan. The Quetta Hills are west oriented. The Sulaiman Range and Kirthar Range are in the south. The *Kirthar Range* is an N–S-trending 400-km-long belt. The NNE–SSW-trending Las Bela Range associated with the Kalat Plateau in southern Balochistan gives way to the *Makran Range* that trends E–W parallel to the coast.

1.2.4 Indus–Ganga–Brahmputra Plain

A significant lithospheric flexure developed on the foothills or south of the rising Himalaya Mountains leading to the deposition of the Cenozoic Siwalik in a foreland basin, filled in subsequently by the Quaternary sediments of the great Himalayan rivers. The vast spread of undulating sedimentary terrain extending from the Indus in the west to the Brahmaputra in the east and Ganga–Jamuna plains in between the two, formed in the foredeep which was created by the rising Himalaya and complete