World Geomorphological Landscapes

Vishwas S. Kale *Editor*

Landscapes and Landforms of India

Springer

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ISSN 2213-2090 ISSN 2213-2104 (electronic)
ISBN 978-94-017-8028-5 ISBN 978-94-017-8029-2 (eBook)
DOI 10.1007/978-94-017-8029-2
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2014939066

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us by creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by Geomorphology—"the Science of Scenery"—a part of Earth Sciences that focuses on landforms, their assemblages, surface, and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume, the third in the series, introduces the geomorphology of India—a vast country with highly diverse landscapes, from the lofty Himalaya to the world's largest delta, and from subtropical mountains in the south to the deserts in the north-west. To do justice to the enormous geomorphological diversity of India in one book is nearly impossible. However, the reader will be helped by an extended Part II of the book in which, after general presentations of tectonic background, timescales involved in landforms evolution, and the climate past and present of the subcontinent, five main geomorphic provinces of India are presented. These are followed in Part III by 18 specific examples of great landscapes stretching from the frigid Ladakh to the subtropical Andaman Archipelago. Nearly four dozen geomorphosites are listed in Part IV of the monograph. Each is worth a special visit and the incoming IX International Conference on Geomorphology in India in 2017 will be a perfect opportunity to do so.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigour, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to the Editor, Professor Vishwas S. Kale, who coordinated the work of many authors from different countries with extreme dedication, enthusiasm, and patience. I am also grateful to all individual contributors who agreed to add the task of writing chapters to their busy agendas and delivered high quality final products.

Piotr Migoń

Foreword

The Indian subcontinent covers approximately 4.5 million km^2 area. In spite of the fact that the Indian landmass is geographically a part of the Eurasian continent, the Indian Peninsula and the Himalayan sector together represent and make up a distinct more than 3 billion years of geologic history. This monograph provides a synoptic view of this diverse, scenic, and ancient landmass.

The Indian subcontinent is composed of incredible variety of landscapes and landforms. It includes the Himalaya—the loftiest mountain range in the world, with some of the longest glaciers, the vast interminable alluvial plains of the Indus, Ganga, and Brahmaputra, the Western Ghat (*aka Sahyadri*)—one of the most spectacular great escarpments of the world, the Deccan Traps—one of the largest igneous provinces in the world, and the Ganga–Brahmaputra Delta—the world's largest delta. The Lonar Crater, one of the youngest and best-preserved impact craters in the world, is located within the Deccan Traps country in the Indian Shield.

Some of the other outstanding landforms of the Indian region are the intermontane basins and valleys of Himalaya (Kashmir, Pinjaur Dun, Dehradun, etc.), the megafans at the foot of Himalaya (such as those of Kosi, Tista, and Gandak), Ladakh—the cold desert north of Himalaya, and the Great Indian Desert known as the Thar Desert. Like other shield areas in the tropics, the Indian Shield is also characterized by vast undulating plains with solitary, dome-shaped (inselbergs) or boulder-strewn (nubbins) hills. Another distinctive landscape located in western India is the Great Rann of Kachchh, an unusually large, saline playa spanning an area of more than 16,000 km^2. The $\sim$7,000 km long coastline of India also displays numerous distinct features. Whereas rocky features dominate the west coast, the eastern seaboard is delta-studded.

The landforms of the Indian subcontinent have been shaped primarily by three factors through time—lithology, tectonic history and climate. The subcontinent is dominated by a large variety of rocks ranging from Archean to Holocene in age. The spectacular granite landforms of the Indian Shield, the stepped landscape of the Deccan Traps region, and the duricrusted landforms display the strong control of lithology. On the subcontinental scale, however, the mega-landforms and drainage owe their present form and disposition largely to the geological and tectonic processes that began with the northward drift of India more than 150 million years (Ma) ago. Once a part of the Gondwanaland, India broke away from it, made a solitary northward journey, and finally collided with Eurasia resulting in the formation of the mighty Himalaya and the vast foreland basin. At least during the last 8–10 Ma the landforms and landscapes of the Indian subcontinent have been fashioned by the Indian monsoon. The unique behavioral characteristics of the Indian rivers could be attributed to the monsoon climate of the region.

The Indian subcontinent also has significant and rich cultural heritage resources. Archaeological and architectural remains indicate that the region has been occupied since early Acheulian times ($\sim$1 Ma). The vast landscape is dotted with countless Palaeolithic, Mesolithic, Neolithic, and Chalcolithic sites and historical settlements as well as numerous ancient temples, monuments, caves, rock sculptures, inscriptions, or monoliths, and Medieval forts. The Harappan civilization, one of the three oldest civilizations of the world, flourished in the Indus Valley ~3.5–1.5 ka BCE (ka = thousand years; BCE = Before the Common Era). Presently (January 2014), there are 30 World Heritage Properties in India, out of which 6 are Natural Properties and 24 are Cultural Properties. In addition, there are over 3,500 protected monuments under the protection of Archaeological Survey of India.

This book with a focus on the landforms and landscapes of India is a part of the recently launched book series *World Geomorphological Landscapes* and is produced under the scientific patronage of the International Association of Geomorphologists (IAG).

The contents of this book are divided into four parts. Part I contains the background about geology and tectonic framework (S. K. Tandon et al.), present and past climate (A. K. Singhvi and R. Krishnan), and the geomorphic provinces and geomorphological history (V. S. Kale). The landscapes of the four major geomorphic provinces are described in slightly greater detail in Part II of the book. These include—Himalaya (L. A. Owen), the Indus–Ganga–Brahmaputra Plains (R. Sinha and S. K. Tandon), the Indian Peninsula (V. S. Kale and R. Vaidyanadhan), and the Thar Desert (A. Kar). The focus of the next chapter (R. Mukhopadhyay and S. M. Karisiddaiah) is on the coastal landforms and processes.

In Part III, 18 specific landscapes and landforms (Fig. 1) are described. This section of the book is organized into a sequence of chapters in a clockwise direction starting from the northern state of Jammu and Kashmir and ending in western India via central, northeastern, eastern and southern India.

The second longest glacier outside the polar regions, namely the Siachen Glacier is described by M. R. Bhutiyani, followed by chapters on the high-altitude cold desert of Ladakh (N. Juyal), the Vale of Kashmir (R. K. Ganjoo) and Sikkim-Darjeeling Himalaya (L. Starkel and S. Sarkar). Two special features of the Himalaya are the occurrence of longitudinal intermontane basins in the frontal zone, called 'Duns' (S. K. Tandon and V. Singh) and numerous megafans (R. Sinha). One of the most famous badlands is observed along the Chambal River in central India (V. U. Joshi) and the Brahmaputra River in Assam is one of the largest braided rivers in the world (J. N. Sarma). The landscape of Meghalaya (Shillong) Plateau is the focus of the next chapter (P. Prokop) and the characteristic features of the Sundarbans and the Ganga–Brahmaputra Delta are explained by K. G. Rogers and S. L. Goodbred Jr.

There are no classic karstic landscapes in India. However, several spectacular caves occur in eastern and northern parts of the subcontinent. A. C. Narayana et al. describe the special characteristics of two well-known karstic caves in eastern India, namely Belum and Borra Caves. Geographically, granite landforms cover vast areas of the Indian Shield. These are dealt with in the chapter by Y. Gunnell.

There are two archipelagos, a little away from the Indian mainland. One of them, the Andaman Archipelago, has been described by J. S. Ray. A prominent feature occurring in some parts of the east coast are the red sand dunes, presently dissected by gullies. The features of such a landscape occurring in the southern state of Tamil Nadu and known as Teri red sands are explained by R. Jayangondaperumal.

In the Deccan Volcanic Province, spectacular laterite-capped tablelands and mesas are present at Panchgani and form the focus of the chapter by V. S. Kale. The unique meteor impact crater in the basalts at Lonar is the main theme of the chapter by M. S. Bodas and B. Sen.

The surreal landscape of the Rann of Kachchh with an enormous stretch of salt-covered marsh is described by Navin Juyal and the special features of the largest playa in the Indian Desert, the Sambhar Lake, are discussed by R. Sinha. The concluding chapter

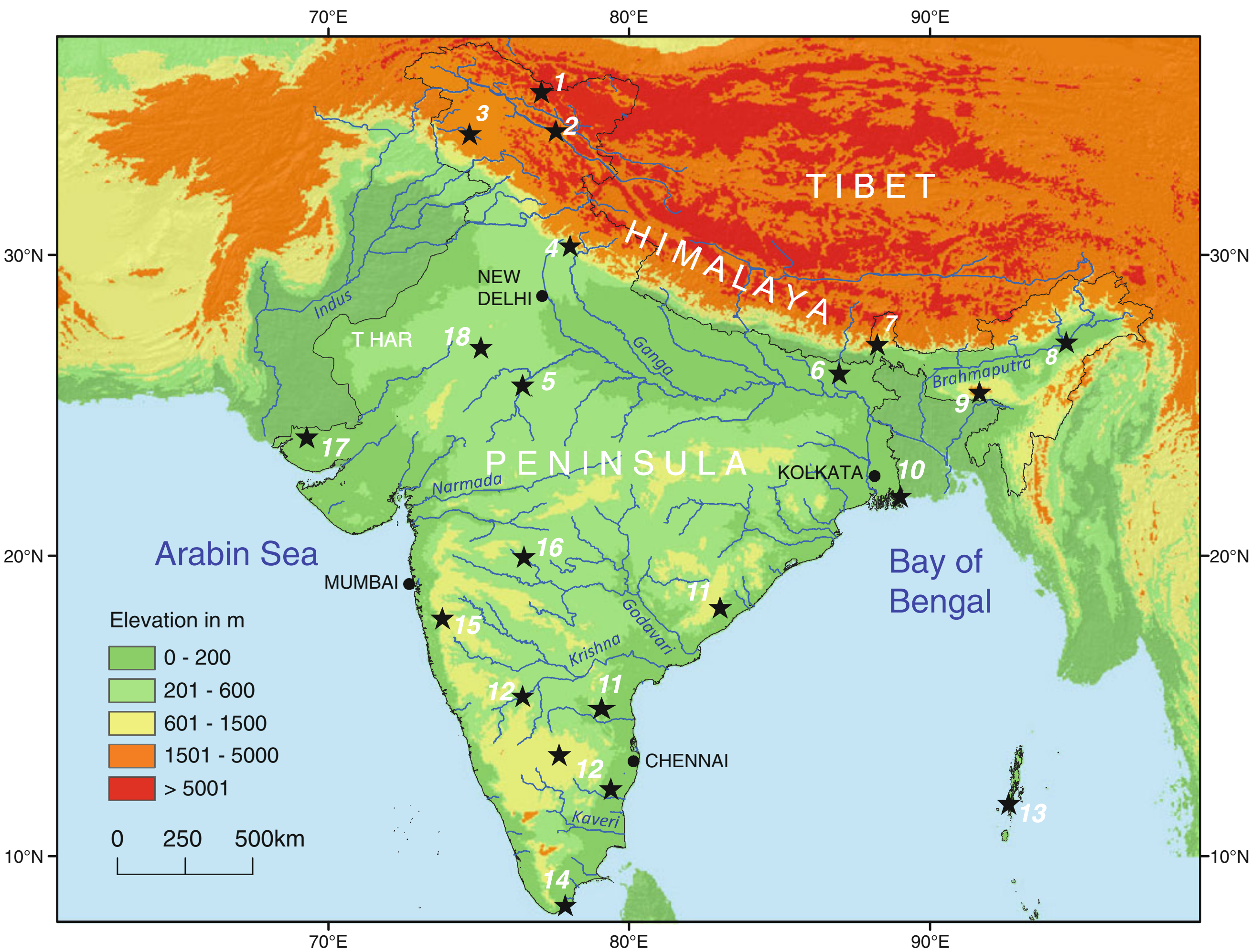

Fig. 1 Physical map of the Indian subcontinent. The map shows the location of 18 specific landscapes or landforms discussed in Part III of this book. 1 = The Siachen Glacier: The Second Longest Glacier Outside the Polar Regions, 2 = Ladakh—The High-altitude Indian Cold Desert, 3 = The Vale of Kashmir—Landform Evolution and Processes, 4 = Duns: Intermontane Basins in the Himalayan Frontal Zone, 5 = The Chambal Badlands, 6 = The Kosi Megafan: The Best known Himalayan Megafan, 7 = The Sikkim-Darjeeling Himalaya—Landforms, Evolutionary History and Present-day Processes, 8 = The Brahmaputra River in Assam: The Outsized Braided Himalayan River, 9 = The Meghalaya Plateau—Landscapes in the Abode of the Clouds, 10 = The Sundarbans and Bengal Delta: the World's Largest Tidal Mangrove and Delta System, 11 = The Spectacular Belum and Borra Caves of Eastern India, 12 = Granite Landforms of the Indian Cratons, 13 = The Andaman Archipelago, 14 = Teri Red Sands, Tamil Nadu, 15 = The Laterite-Capped Panchgani Tableland, Deccan Traps, 16 = The Lonar Crater—The Best Preserved Impact Crater in the Basaltic Terrain, 17 = The Great Rann of Kachchh: The Largest Saline Marshland in India, and 18 = The Sambhar Lake: The Largest Saline Lake in Northwestern India

of the monograph (V. S. Kale) constitutes Part IV and gives a list of four dozen potential geomorphosites in India.

This book could not have seen the light of the day without the help and support of several individuals. At the outset, I would like to express my profound thanks to Piotr Migoń, the Series Editor, for inviting me to edit this volume on India and for his guidance at every stage. He provided valuable comments that considerably improved the clarity and quality of the chapters. Special thanks are also due to Robert Doe and M. Agila of Springer for their constant support and guidance.

I would also like to express my sincere and heartfelt thanks to all the authors for their alacrity with which they responded to my invitation and for sending in their contributions for the monograph. My very special words of thanks are to R. Vaidyanadhan for reviewing

some of the chapters and for his valuable inputs at every stage. I am also thankful to Sandip Pawar and Nilesh Susware for redrawing some of the figures. Navin Juyal, Yanni Gunnell, Lewis Owen, Amal Kar, S. N. Rajaguru, Bob Wasson, K. N. Prudhvi Raju, Sunando Bandyopadhyay, L. S. Chamyal, Nilesh Bhatt, and N. Basavaiah have contributed to this monograph in various ways. I thank them profusely.

Pune, India, May 5, 2014 Vishwas S. Kale

Contents

Part I

Physical Environment and Geomorphic History

Geological and Tectonic Framework of India: Providing Context to Geomorphologic Development

Sampat K. Tandon, Partha Pratim Chakraborty and Vimal Singh

Abstract

Surrounded by the Himalayan Orogen, Indian Ocean, Bay of Bengal and Arabian Sea on its north, south, east and west, respectively, the Indian subcontinent represents more than 3.5 Ga of geological history spanning from the Archean to Quaternary. The exposed Precambrian basement of India comprises four Archean cratonic nuclei welded together by several Proterozoic mobile belts. Proterozoic intracontinental basins that contain mostly undeformed sedimentary successions unconformably overlie the basement. The basement rocks are covered in the north along the Himalayan front by thick deposits of the Indo-Ganga alluvium, and in the west central region by the end-Cretaceous Deccan flood basalts. Basins related with intra- to inter-continental rifting of the Indian craton viz. the Gondwana Basins and those of the east and west coast record the Phanerozoic history of India from Permian to Cenozoic. Since ~ 55 Ma, the continent-continent collision between the northerly drifting Indian Plate and the Eurasian Plate has guided the development of the structural design of the Himalayan Orogen. These tectono-geomorphic processes were responsible for the first order relief structure of the northern part of the Indian subcontinent including the development of the topography of the spectacular Himalayan Orogen and its foreland.

Keywords

Geology • Tectonic framework • India • Craton • Peninsula • Himalaya • Indo-Ganga plains

1 Introduction

The Indian region represents a peninsula in south Asia that is girdled by the Himalayan Orogen in the north, extends southward into the Indian Ocean, and is bordered by the Bay of Bengal and the Arabian Sea in its southeast and southwest, respectively (Fig. 1). It forms a part of the Indo-Australian Plate; one of the six major plates of the globe with an area of ~ 12 million km^2. Broadly, three physiographic subdivisions viz. the Peninsula, the Indo-Ganga Basin, and the Himalaya constitute the Indian subcontinent. The geological structure of the Peninsula evolved through the welding of Archean cratonic nuclei by several Proterozoic mobile belts as a result of multiple orogenic cycles ranging in age from the Paleoproterozoic to early Palaeozoic; the Himalaya and the

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V. S. Kale (ed.), *Landscapes and Landforms of India*, World Geomorphological Landscapes,
DOI: 10.1007/978-94-017-8029-2_1,

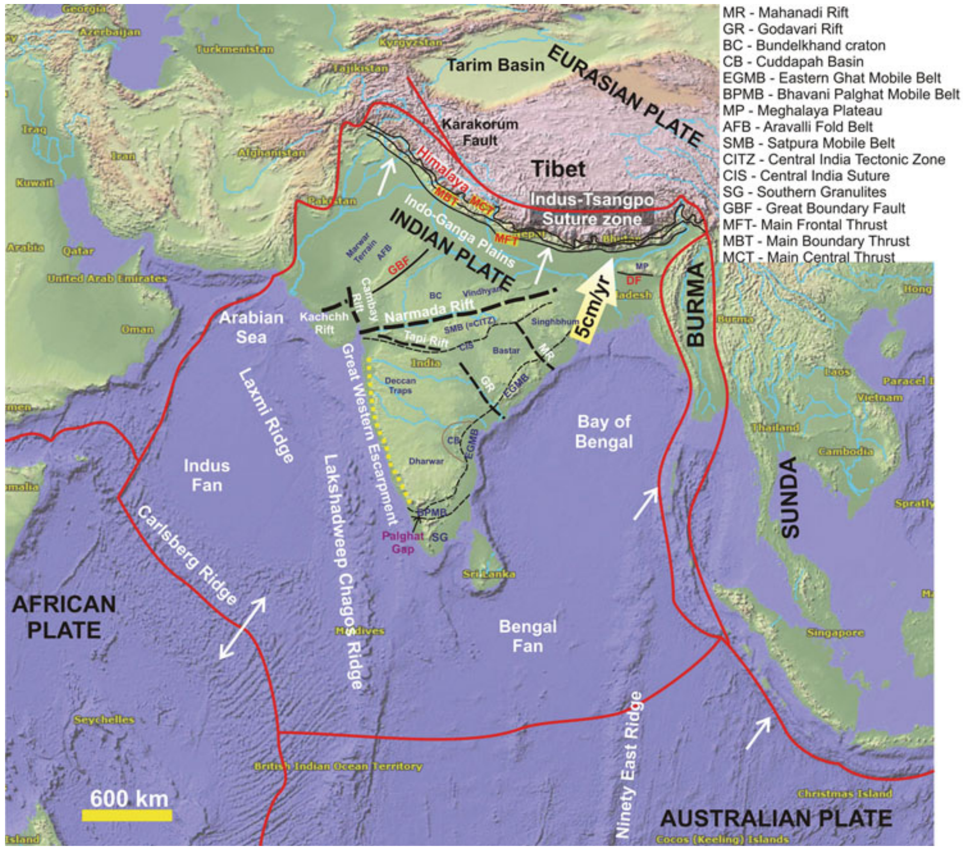

Fig. 1 Map showing tectonic framework of the Indian Plate with major regional physiographic features (base map taken from 3D world map)

Indo-Ganga (Indo-Gangetic) Basin evolved in response to the northward migration of the Indian Plate in the Cenozoic and collisional orogenesis involving the Indian Plate and the Eurasian Plate (Fig. 1).

The geological history of Peninsular India can be traced back to the Archean, a time when the early Earth was characterized by the formation of proto-continents of sialic composition. Proterozoic basins are well developed in various parts of the Peninsula, and some of these basins in the northern part of the Indian craton have been involved in the Himalayan Orogeny and now constitute an integral part of the Lesser Himalaya. Apart from some Early Cambrian strata, the earliest Phanerozoic geological record of Peninsular India is found in the rift-related Permian to Cretaceous coal bearing basins i.e., the Gondwana Basins. Because of the tectonic reactivation resulting from the Cenozoic uplift in the Himalaya and the Deccan Volcanism related plateau uplift, the landscapes in the Peninsula consist of several high-level geomorphic surfaces that show variable degrees of dissection.

In the Late Cretaceous, the Indian Plate split from Madagascar and began its northward journey at a rate of about 20 cm per year. A number of late Triassic to early Cretaceous basins located at the margin of the Indian Shield preserve the record of extension and subsidence of the Indian crust below the Neo-Tethys Sea in the north. Later, in the early Palaeogene the Indian Plate started its convergence below Asia; its leading edge dipped northwards and north-eastwards to be underthrusted beneath the Asian landmass. The collisional tectonics commenced $\sim$50 to 55 Ma (million years) back and led to the initiation of the Himalayan Orogenic Belt. Southward propagating thrust sheets formed the Himalayan chain consisting of four main litho-tectonic units from the north to the south. Collisional tectonics took place through the Cenozoic in the Himalaya and is ongoing as evidenced by major seismicity all along the Himalayan arc in the Holocene and in the historical period. Continued underthrusting of the Indian Plate resulted in a thick (60–70 km) crust in the Himalayan region. Also, the continued loading of the lithosphere in the Himalayan thrust belt was accompanied by lithospheric flexure and the formation of a peripheral foreland basin—the Himalayan Foreland that extends along almost the entire southern flank of the orogen.

The Himalayan Foreland has acted as a loci of sediment accumulation from the Palaeogene, through the Neogene and into the Quaternary. This basinal fill has been deformed and uplifted into the Siwalik Hills in the outer Himalaya; the relatively distal and undeformed part of the basin constitutes the Indo-Ganga Basin whose surface expression corresponds with the major geomorphic units of the Indo-Ganga Plain. This Plain is a prominent feature on the surface of the globe, occupies an area of $\sim$700,000 km^2, and

Table 1 A generalized stratigraphic framework for Peninsular and Extra-Peninsular India

		Peninsular India			Extra-Peninsular India
Phanerozoic	Quaternary	Indus, Ganga and Brahmaputra River Valleys, Coastal Tracts and Thar Desert			
	Cenozoic	Gujarat mainland, Saurashtra, Kachchh, Jaisalmer and Barmer Basins, Niniyur Formation, Baripada beds, Chhotanagpur Plateau	Northeast India Tipam Barail	Andaman-Nicobar basin	Siwaliks Kasauli Dagshai Subathus
	Mesozoic	*Rifting and formation of Coastline*			Collision and Himalayan uplift (∼55 Ma)
		West Coast	*East Coast*		
		Kerala Basin, Konkan Basin	Bengal basin, Mahanadi basin		
		Mumbai Basin, Saurashtra Basin	Krishna-Godavari Basin, Palar Basin		
		Kachchh basin		Mesozoic Basins of Rajasthan (Kachchh and Jaisalmer Basins)	Abor volcanics Gondwanas in Bhutan and NE Himalaya
		Deccan Traps (68–60 Ma)			
		Rajmahal Trap Intracratonic rifting (Gondwanas) Pranhita-Godavari valley, Son-Mahanadi valley, Damodar-Koel valley			
	Palaeozoic				Tethyan sub-basins (i) Kashmir sub-basin (ii) Spiti-Zanskar sub-basin (iii) Garhwal-Kumaun sub-basin
Precambrian	Proterozoic	*Intracratonic to epicratonic Basins*	*Mobile belts*	*Rifts*	
		(i) Vindhyan (ii) Chhattisgarh (iii) Cuddapah (iv) Pranhita-Godavari (v) Kaladgi–Bhima (vi) Marwars etc. (1899 ± 20 Ma to ∼543 Ma)	CITZ (2.2–1.5 Ga) Eastern Ghat mobile belt (1.6–0.58 Ga) Pandyan mobile belt (0.75–0.55 Ma) Aravalli-Delhi mobile belt	Godavari Mahanadi Son-Narmada	Higher Himalaya Lesser Himalaya
	Archean	*Cratonic nuclei*			
		(i) Dharwar (3.4–2.5 Ga), (ii) Bastar (3–1.8 Ga), (iii) Singhbhum (3.4–1.6 Ga), (iv) Bundelkhand (3.3–1.8 Ga)			

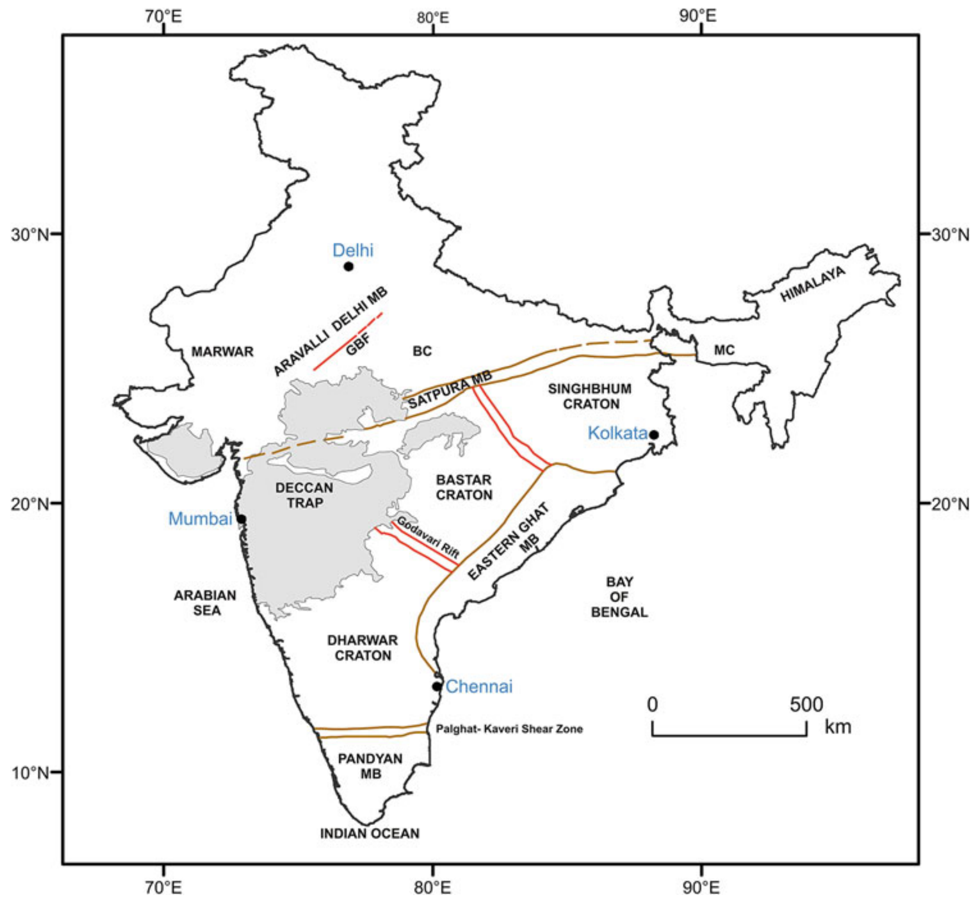

Fig. 2 Cratonic nuclei, marginal mobile belts and pericratonic rift systems of Peninsular India (modified after, Ramakrishnan and Vaidyanadhan 2010). *Dashed lines* suggest inferred extension of the faults. BC—Bundelkhand Craton; MC—Meghalaya Craton; GBF—Great Boundary Fault; MB—Mobile Belts

occurs in between the Indian Peninsula and the Extra-Peninsular or Himalayan Orogenic Belt. This alluvial plain slopes to the east-southeast and receives detritus both from the glacier-fed Himalayan rivers and those flowing from the positive cratonic areas in the south.

The Indo-Ganga Plain is flanked in its south by the craton-related positive areas of the Indian Peninsula, and to its west by the Thar Desert. Many of the orogenic belts of the Peninsula are morphologically expressed as hill ranges such as the Aravalli, Sahyadri, etc. Also, the Peninsular region is marked by plateaus, for example the Deccan Plateau covering an area of about half a million square km in the western and the central parts of the country, coastal lowlands in the eastern and western parts, and major deltas formed by west to east flowing major drainages whose origins have been connected to the plume-related uplift of the Deccan Volcanic Province (Cox 1989).

2 Broad Stratigraphic Framework of Peninsular India

Table 1 summarizes the general stratigraphic framework for Peninsular and Extra-Peninsular India. Tectonically, at a first order, Peninsular India consists of cratons and mobile belts that are curvilinear high-grade gneiss-granulite terrains surrounding the cratonic nuclei (Fig. 2).

The Indian Shield has been considered to be made up mainly of four cratons (1) Dharwar, (2) Bastar, (3) Singhbhum, and (4) Bundelkhand, and four mobile belts i.e. the Eastern Ghat mobile belt fringing the Dharwar, Bastar, and Singhbhum Cratons; the Pandyan Mobile Belt fringing the Dharwar Craton, the Satpura Mobile Belt fringing the Bastar, Singhbhum, Bundelkhand Cratons (Ramakrishnan and Vaidyanadhan 2010) and the Aravalli-Delhi Mobile Belt (ADMB) fringing the Bundelkhand Craton (Fig. 2). Radhakrishna and Ramakrishnan (1988) divided the Indian Shield along the Narmada-Son Lineament into a northern and southern block, each of which consisted of welded cratonic nuclei.

These old cratons and mobile belts that constitute the major part of the shield are succeeded by a younger cover, components of which are listed below (Ramakrishna and Vaidyanadhan 2010):

(1) Proterozoic sedimentary basins, also known as the Purana Basins, ranging in age from the mid-Proterozoic to the terminal Proterozoic
(2) Gondwana sedimentary basins in the Damodar, Satpura, Narmada-Tapti, Mahanadi, Krishna-Godavari rifts, ranging in age from the Permian to the Cretaceous,

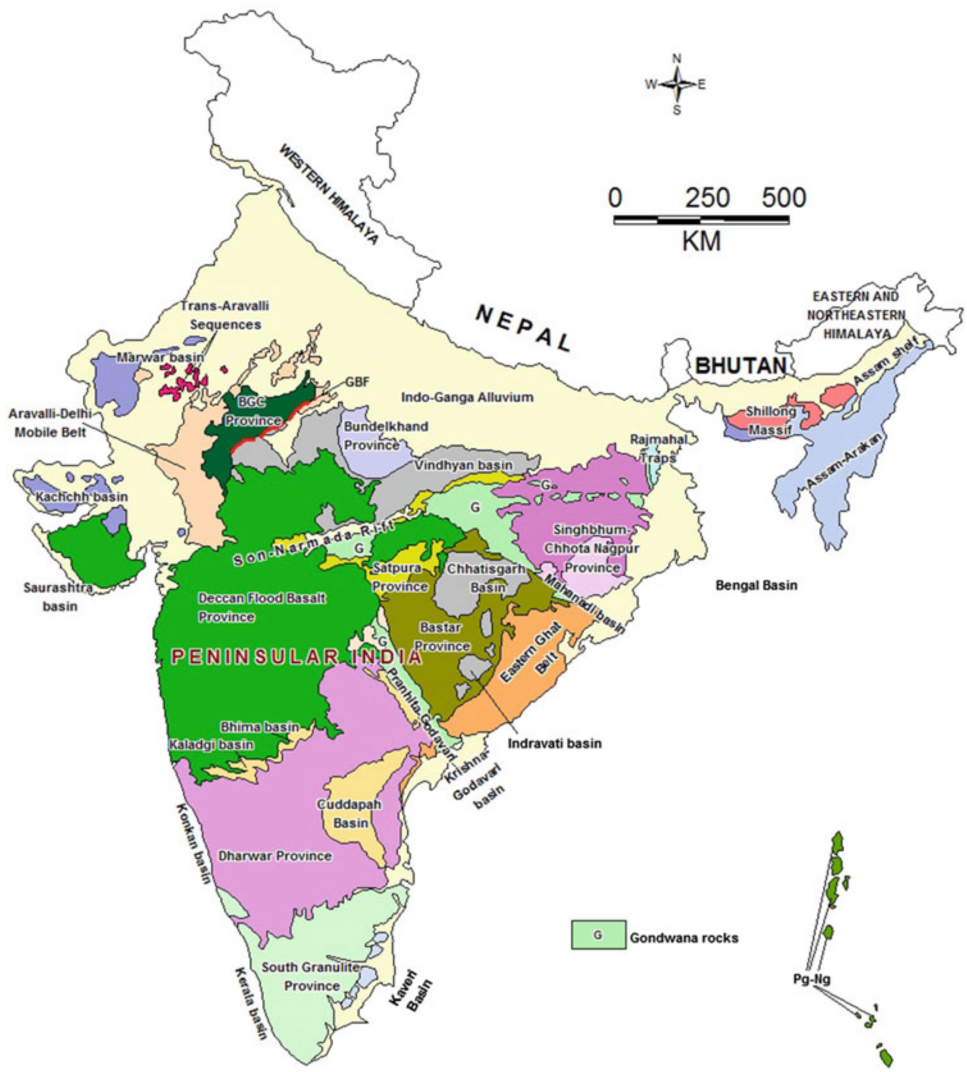

Fig. 3 Simplified map showing the geological provinces of Peninsular India (after Chakrabarti et al. 2006). BGC—Banded Gneissic Complex; GBF—Great Boundary Fault; Pg-Ng—Unclassified Paleogene-Neogene.

along with the Permian marine incursions marked by the occurrence of Umaria and Manendragarh marine beds

(3) Rajmahal Volcanic Province dating to ~115 Ma in eastern India

(4) Deccan Volcanic Province, a Late Cretaceous large igneous province in western and central India with the bulk of the volcanic activity being centered around the K-T (Cretaceous-Tertiary) boundary

(5) Cretaceous marine incursions in the Narmada region and in the Kaveri Delta, for example the well known Trichnopoly Beds

(6) Mesozoic-Cenozoic successions of Western Rajasthan, Kachchh and Saurashtra

(7) Late Quaternary alluvial sequences along the major river valleys of the Indian Peninsular, for example, Narmada, Son, Tapi, Ken, Betwa, Kaveri, Krishna-Godavari; as well as the Late Quaternary delta sequences along the east coast of India.

3 Precambrian Crustal Evolution of Peninsular India

The Precambrian geological history of the Peninsular India spans three billion years. The Precambrian shield comprises of Archean cratons, Proterozoic mobile belts and shear zones, and continental rifts such as Narmada-Son, Godavari and the Mahanadi Rifts (Figs. 2 and 3). The cratonisation of India was polyphase, and a stable configuration of the assembly was completed by ~2.5 Ga (Meert et al. 2010). Several Meso- to Neoproterozoic Purana Basins that include the Cuddapah, Chhattisgarh, Vindhyan, Pranhita-Godavari, Indravati, Bhima-Kaladgi, Kurnool, and the Marwar basins cover the Archean-early Proterozoic terrains, and are spread over many parts of the Indian landmass (Figs. 2 and 3).

3.1 Cratons, Purana Basins, and the Southern Granulite Terrain (SGT)

(a) The Bundelkhand Craton: The Great Boundary Fault (GBF) demarcates the boundary between the Bundelkhand protocontinent and ADMB in its west (Figs. 2 and 3). A crustal-scale lineament, namely the Narmada-Son lineament separates the Bundelkhand Craton and the ADMB to its north from the Bastar and Singhbhum Cratons to its south (Naqvi and Rogers 1987). The supracrustal rocks of the Aravalli-Delhi Fold Belts overlie the 3.3 to 2.5 Ga old Banded Gneissic Complex (BGC), and their ages are considered between ~1850 and 2150 Ma (Meert et al. 2010). Metamorphism in two stages i.e. between 1620 and 1725 Ma, related to the beginning of the Delhi Orogenic cycle (Roy et al. 2005), and at ~950 Ma (Buick et al. 2006) affected rocks of the Aravalli-Delhi Fold Belt. Following these events, the Malani felsic extrusive and intrusive igneous activity took place between 750 and 800 Ma (Gregory et al. 2009). These rocks constitute a part of the basement for the unconformably overlying Neoproterozoic Marwar Supergroup in western Rajasthan. The Bundelkhand Craton has been divided into three litho-tectonic units (1) Archean enclaves constituted by highly deformed older gneissic-greenstone components, (2) undeformed granitoid plutons and associated quartz reefs, and (3) mafic dyke swarms and other intrusions. The Bundelkhand Granite has yielded an age of ~2492 Ma (Mondal et al. 2002). The mafic dykes that intrude the Bundelkhand Igneous Complex have yielded ages of 2.15 and 2.0 Ga, respectively (Mallikharjuna Rao 2004).
The intracratonic Marwar Basin of Neoproterozoic-Palaeozoic age occurs to the west of the Aravalli fold belt and the Vindhyan Basin of central Peninsular India to the west and south of the Bundelkhand Craton. The sickle-shaped Vindhyan Basin occurs between the Aravalli-Bundelkhand Province in the north and west and the Late Cretaceous Deccan Traps in the south; the Great Boundary Fault marks the western limit of this basin. Stratigraphically, the Vindhyan Basin comprises of a Lower Vindhyan Semri Group unconformably overlain by an Upper Vindhyan sequence consisting of the Kaimur, Rewa, and Bhander Groups. The geochronology of the Semri Group is based on a Pb-Pb isochron from the Lower Kajrahat Limestone of ~1721 Ma (Sarangi et al. 2004) and U-Pb ages from the porcellanites ranging from ~1630 to 1599 Ma. Most workers subscribe to a Paleo-Mesoproterozoic age for the Lower Vindhyan sedimentation.

Fig. 4 A panoramic view of the Dharwar granulite terrain (Photo courtesy of M. Jayananda)

(b) The Singhbhum Craton: This craton lies in the central and eastern part of India and consists of several assemblages that include the Older Metamorphic Group, the Singhbhum Granite, and the Iron Ore Group (IOG). It is bordered to the north by the Chhotanagpur granite-gneiss terrain (CGGT) which is considered to be an extension of the Central Indian Tectonic Zone (CITZ). The Singhbhum nucleus is composed of Archean granitoid batholiths, including the Singhbhum granite complex (Meert et al. 2010). The oldest enclaves within the batholiths are the Older Metamorphic Group (OMG) which has yielded U-Pb zircon ages of 3.5, 3.4, and 3.2 Ga. The OMG is intruded by the Singhbhum granite complex that consists of several domal magmatic bodies which range in age from 3100 to 3500 Ma. In the Singhbhum Craton, the Iron Ore Group marks the greenstone-gneiss terrain. Further, gneissic complex rocks of ~2.6 Ga, correlative with the OMG, recorded from Shillong-Mikir Hills Plateau in the northeastern part of India are also referred occasionally as 'Meghalaya Craton' (Sharma 2009).
The Palaeo-Mesoproterozoic sequences of the Singhbhum Craton include the Dhanjori Formation, the Chaibasa Formation, and the Dhalbhum, Dalma, and Chandil Formations. The Dhanjori Formation, representing the oldest (~2.5 to ~2.85 Ga) sedimentary basin in this craton consists of an assemblage of clastic, mafic-ultramafic volcanic, and volcaniclastic rocks (Mazumder 2005). The youngest of these Mesoproterozoic sequences, the Chandil Formation is probably older than ~1638 Ma (Mazumder 2005). In the southern part of this craton, the Kolhan Group, ~1.1 Ga in age, occurs as a transgressive sequence and has been related to the fragmentation of the Rodinia Supercontinent (Mukhopadhyay et al. 2006).

Fig. 5 A prominent escarpment in Pachmarhi sandstone of the Gondwana landscape, Satpura Belt. (Photo courtesy of Tapan Chakraborty)

(c) Bastar Craton: This craton, also referred to as the Central Indian Craton and the Bhandara Craton, consists of supracrustal sequences, mafic dyke swarms, and the Satpura Orogenic Belt (Naqvi and Rogers 1987). Ramakrishna and Vaidyanadhan (2010) pointed out that there are Tonalite-Trondjhemite Gneiss (TTG) assemblages dated to 2.5–2.6 Ga indicating a major period of crustal accretion. The Bastar Craton is intruded by several dyke swarms that cross cut the granitoids and the supracrustal sequences viz. the Dongargarh, the Sakoli, and the Sausar. The Bastar Craton is host to two major Mesoproterozoic Basins, the Chhattisgarh and the Indravati Basins.

(d) The Dharwar Craton: The Dharwar Craton (Fig. 4) is commonly subdivided into the Eastern and Western Dharwar Cratons. The Eastern Dharwar Craton (EDC) is composed of the Dharwar Batholith, greenstone belts, intrusive volcanics, Mesoproterozoic and younger sedimentary basins (Naqvi and Rogers 1987; Ramakrishnan and Vaidyanadhan 2010). The Western Dharwar Craton (WDC) consists of three generations of volcano-sedimentary greenstone-granite sequences i.e. the 3.1–3.3 Ga Sargur Group, the 2.6–2.9 Ga Dharwar Supergroup and the 2.5–2.6 Ga calc-alkaline to high potassic granitoids (Meert et al. 2010 and references therein).

Proterozoic sedimentation in the Dharwar Craton took place in the Cuddapah, Pranhita-Godavari, and Bhima Basins. The Cuddapah succession is estimated to be 12 km thick and is made up of two units—the Cuddapah Supergroup present throughout the basin and an unconformably overlying Kurnool Group limited to the western part of the basin. A thermal event at ~1.9 Ga has been suggested for the initiation of the Cuddapah Basin. The Pranhita-Godavari Basin occurs between the Dharwar and the Bastar Cratons (Fig. 2), and consists of several unconformity-bounded packages adding up to ~6 km in thickness. These range in age from ~790 to 1330 Ma. The Bhima Basin is made up predominantly of calcareous facies.

(e) Southern Granulite Province: In addition to these cratons, a prominent feature of the geology of southern India is the Southern Granulite Province (SGP) which is considered to be made up of three late Archean to Neoproterozoic high grade metamorphic blocks that are joined together by a series of shear zones (Figs. 2 and 3). The Northern Block (NB) is separated from the Central Block (CB) by the Moyar-Bhavani Shear Zone. The Central Block is divided further into a western Nilgiri Block and an Eastern Madras Block. The Madras Block is bounded by the Palghat-Cauvery Shear Zone (PCSZ), and is followed southwards by the Madurai Block. The NE-SW trending Achankovil Shear Zone (ACSZ) separates the Madurai block from the southernmost Trivandrum Block (Naqvi and Rogers 1987; Ramakrishnan and Vaidyanadhan 2010).

Availability of well-constrained geochronological data, in the last two decades, allowed the delimitation of tectono-thermal events in craton-margin orogens and helped in understanding the forcing of such events in shaping the architecture of the Indian Peninsula. The most conspicuous early Paleoproterozoic (2.45–2.48 Ga) high grade metamorphism in the Indian crust is recorded from Nilgiri, Savoy Hill massifs and from the Palghat-Cauvery Shear Zone. The Aravalli Orogeny is considered to have closed around 1850 Ma. Unambiguous evidence for the Paleoproterozoic (1.6 Ga) ultrahigh temperature metamorphism at lower

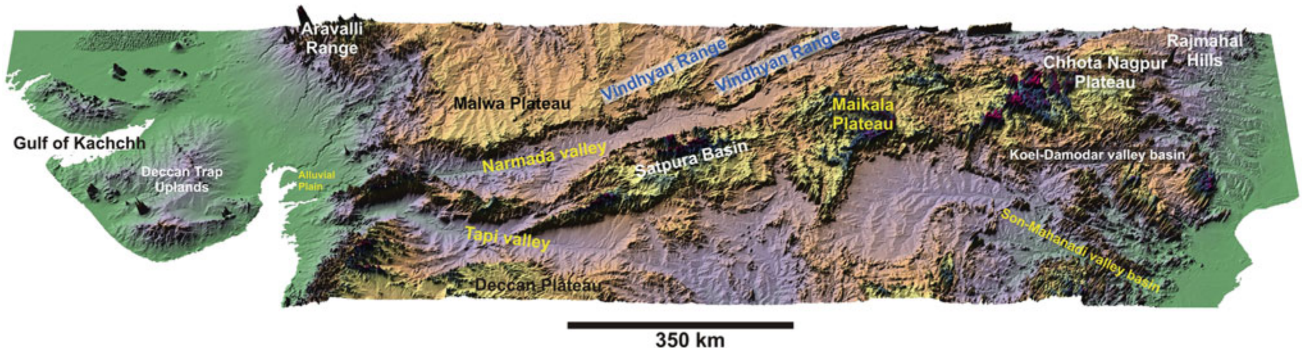

Fig. 6 Physiographic map of the central India showing distribution of Gondwana Basins

crustal depths is available from parts of the Central Indian Tectonic Zone (CITZ), Chhotanagpur Gneissic complex (CGC, 1.72 Ga) and within the southern part of the Eastern Ghat Belt (EGB; 1.76 Ga). It has been suggested that during the period 1.7–1.76 Ga, the EGB was behaving as an accretionary orogen with the development of fold-thrust belt at the craton margin. Also, there is a growing body of evidence in favour of the occurrence of major early Mesoproterozoic tectono-thermal and tectono-magmatic events in Peninsular India, which has resulted in speculations about a Pan-Indian Mesoproterozoic orogen, extending probably to North China, Australia and East Antarctica.

4 Rifting of Craton, Gondwana Sedimentation and Trap Volcanism

The Gondwana sediments (Fig. 5) accumulated in different areas of Peninsular India between Permo-Carboniferous and Triassic (290–208 Ma) and mark the resumption of sedimentation in the Peninsula in late-Carboniferous after a long hiatus (Veevers and Tewari 1995). Three well defined linear belts viz. the NW-SE trending Son-Mahanadi Valley and Pranhita-Godavari Valley Basins, and the east-west trending Damodar-Koel Basin demarcate the structural trends of the Gondwana Basins (Figs. 3 and 6) and are considered as relics of the original master basin that extends below the Cenozoic cover of the Bengal Basin to the coal belts of Bangladesh. The basins are typically bounded by faults that developed along Precambrian lineaments, and are also affected by intra-basinal faults indicating fault-controlled syn-sedimentary subsidence. The glaciogenic Talchir and the overlying coal-bearing Barakar Formations represent the lower part of the Gondwana succession showing uniform characteristics in all the basins. Overlying the pre-Gondwana metamorphics, the glaciogenic Talchir sedimentation comprises of glacial and glacial outwash (glacio-fluvial) deposits. A few beds containing marine fossils within the Talchir Formation indicate an early Permian marine incursion (Veevers and Tewari 1995). With the onset of humid climate two coal measures, the Barakar and Raniganj Formations, succeed the Talchir deposits. A fluvio-lacustrine sequence, devoid of coal and known as Iron Stone Shale (Barren Measure) separates the two coal measures. Rocks of the Panchet Formation, also barren of coal, overlie the Raniganj Formation and comprise of alluvial deposits formed in a semi-arid environment. The eruption of basaltic lava in Early Cretaceous (120–116 Ma) time over a vast stretch of land spanning from Rajmahal in the east to Sylhet region in north-eastern Bangladesh through Meghalaya in between marks the final phase of Gondwana sedimentation.

The Indian Shield, in particular in its central and western part, witnessed voluminous continental flood basalt eruptions in the form of Deccan Volcanics in Late Cretaceous time (Fig. 7). Present day areal extent of this province is 5×10^5 km^2 (Fig. 3) and its original areal extent is estimated at 1.5×10^6 km^2. Expressed as stepped hills, the Deccan lava pile represents its thickest development ($\sim$2000 m) along the Western Ghat region (*Sahyadri*) and thins progressively eastward and southeastward to a thickness of 200 m. Both plume-related and non-plume plate tectonic models are invoked for the interpretation of such a large igneous province like Deccan, which otherwise is considered to be related with rifting and breakup of the Seychelles Micro-continent from India in Late Cretaceous time (Sheth 2005). At places, the volcanic rocks are underlain by Cretaceous sediments that are described as infra-trappeans. In particular, the unique geomorphology of the west coast of India, consisting of elevated inland plateaus, erosionally controlled escarpment, coast parallel monoclinal flexure and the low lying coastal lowland, is interpreted as the response to the combined effects of several factors including shoulder uplift in a rift system, lateral scarp retreat, differential denudation of varying lithologies and flexural isostasy (Fig. 8; Gunnell and Fleitout 2000).

Fig. 7 A regional view of Deccan Traps exposed along the Western Ghat near Lonavala (Photo courtesy of Vishwas S. Kale)

5 Establishment of Indian Continental Margins

The continental breakup processes in East Gondwanaland involving India, East Antarctica, Madagascar and the Seychelles also have left their imprints on the evolution of the continental margins of India, which can be grouped under three different time windows: (a) 250–140 Ma breakup between Africa and the combined India-Madagascar, and its relation with the evolution of certain parts of the western continental margin of India (b) 140–100 Ma India-Antarctica breakup and the development of a passive margin along the east coast of India, and (c) 100–50 Ma India-Madagascar-Seychelles breakup and the development of some parts of the western continental margin of India. Segmented by sub-crustal tectonic elements, five major onshore pericratonic rift basins viz. the Kaveri, Palar, Krishna-Godavari, Mahanadi and Bengal basin, constitute the 2000 km long east coast of India, and are related with their corresponding thick offshore sedimentary depocenters. Towards southeast of the Indian mainland, the Andaman deepwater basin, involving Andaman-Nicobar (Island) accretionary complex in its forearc and the Andaman Sea at its back-arc, represent the arc-trench region in an active plate boundary between the Indian Plate and the Eurasian Plate. The records of rift-drift events related to the separation of Madagascar during the mid-Cretaceous and the Seychelles in Late Cretaceous from India are preserved in five major basins along the western margin of India viz. Kachchh, Saurashtra, Mumbai, Konkan and Kerala. The basins evolved through sequential rifting from north to south under the dominant influence of Dharwar trend (NW-SE to NNW-SSE), the Aravalli trend (NE-SW) and the Satpura trend (ENE-WSW to E-W). According to Biswas (1987), late Triassic rifting in the northern part of the west coast gave rise to three Mesozoic marginal rift basins in the onshore i.e., Kachchh, Narmada and Khambhat (Cambay) that preserve Mesozoic sediments of varying thickness.

Besides, the pericratonic basin of Rajasthan at the northwestern front of the Indian Shield preserves the record of Indus shelf sedimentation in its eastern extension. The basin hosts several sedimentary packages ranging in age from the Precambrian to Tertiary and is internally divided by structural elements into three sub-basins viz. Bikaner-Nagaur in the north, Jaisalmer in the middle, and Barmer-Sanchor in the south.

6 Cenozoic Flight of Indian Peninsula, Closure of Tethyan Sea and Uplift of the Himalayan Orogen

At ~130 Ma the Indian Plate was detached from Gondwanaland and started its northward journey resulting in subsequent closure of the Tethys Sea. The occurrence of island arc complexes in the suture zone between the Indian and the Eurasian Plates bears the imprint of island arc volcanism that was associated with the leading edge of the subducting Neo-Tethyan oceanic crust in the Late Jurassic and Early Cretaceous time. The volcanic arc, presently represented by a thick sequence of the Kohistan Complex in northern Pakistan, and Ladakh Batholith and related rocks to the east of Nanga Parbat, collided along the Indus Suture at the time of closure of the Neo-Tethys. Calc alkaline granite (e.g. Kohistan Batholith of 150 Ma and 85–26 Ma ages and equivalent Ladakh Granite) form a significant part of the island arc complex which also includes metamorphic, plutonic, volcanic and sedimentary rocks (Bouilhol et al. 2010). The structural evolution of the Himalayan Orogen initiated with continent-continent collision between the Indian and the Eurasian Plates in the early Eocene at ~55 Ma. The decrease in spreading rate in the Central Indian Basin from 8 cm/year to 4 cm/year, concomitant slowing down of the Indian Plate velocity from ~18–20 cm/year to ~5 cm/year (Kumar et al. 2006) and the change in the spreading direction from N-S to NE-SW constitute the evidence for this collision event. The formation of the Indus and Bengal Fans in the northern Indian Ocean also began sometime in the Oligocene (Curray and Moore 1971). It is generally agreed upon that the docking between the two plates is diachronous along the strike of the Himalayan Orogen. Evidence from the north-western edge of the Indian Plate suggests it occurred at ~65 Ma (Beck et al. 1995), whereas studies from the Zanskar and Ladakh regions constrain the collision ages to around 52 and 49 Ma. In spite of displaying first order similarities, the Himalaya varies along its strike in deformation styles, uplift-erosion characteristics, and in morphotectonic evolution. Additionally, at the eastern and western

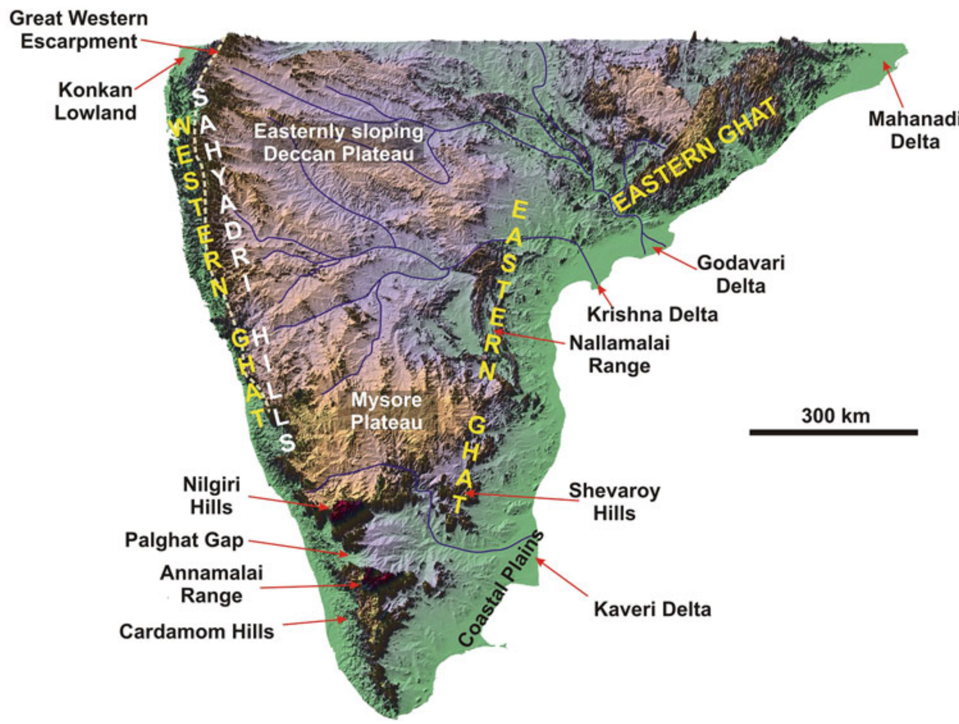

Fig. 8 Physiographic map of a part of Peninsular India showing first order relief structure viz. hills, plateaus, and deltas

Fig. 9 Panoramic view of a part of the Himalaya in Alaknanda Basin showing Lesser Himalaya (*LH*) with snow-covered Higher Himalayan (*HH*) mountains in the background

extremities of the Himalaya, syntaxial bends have been formed.

Stratigraphically, the Himalayan Orogen includes rocks spanning from the Precambrian to Holocene time. In the northwestern Himalaya, the orogen is subdivided into four litho-tectonic units juxtaposed along north-dipping thrust faults. From north to south, these are—(i) Tethyan Himalaya representing Proterozoic to Eocene sediments interbedded with Paleozoic and Mesozoic volcanics and batholiths, (ii) Greater (or Higher) Himalaya (Fig. 9) composed of crystallines, schists, gneisses and granites, (iii) Lesser Himalaya (Fig. 9) composed of Precambrian and minor Paleozoic strata, and orthogneisses, and (iv) Sub-Himalaya constituted of Cenozoic sequences including the Neogene continental Siwalik strata (Fig. 10). The thrust faults that demarcate the boundaries of these units are the South Tibetan Detachment (STD; separating Tethyan and Higher Himalaya), the Main Central Thrust (MCT; separating the Higher and Lesser Himalaya), the Main Boundary Thrust (MBT; separating the Lesser and Sub-Himalaya), and the Main Frontal Thrust (MFT; separating the Sub-Himalaya and Indo-Ganga Plain) (Fig. 10).

The poorly fossiliferous carbonate and siliciclastic sequences in both the Tethyan and Lesser Himalayan are assigned Proterozoic to early Cambrian age and are considered as the record of pre-rift sedimentation history in an epicratonic marine setting on the northern Indian margin (Valdiya 2010). Low to high grade metamorphosed

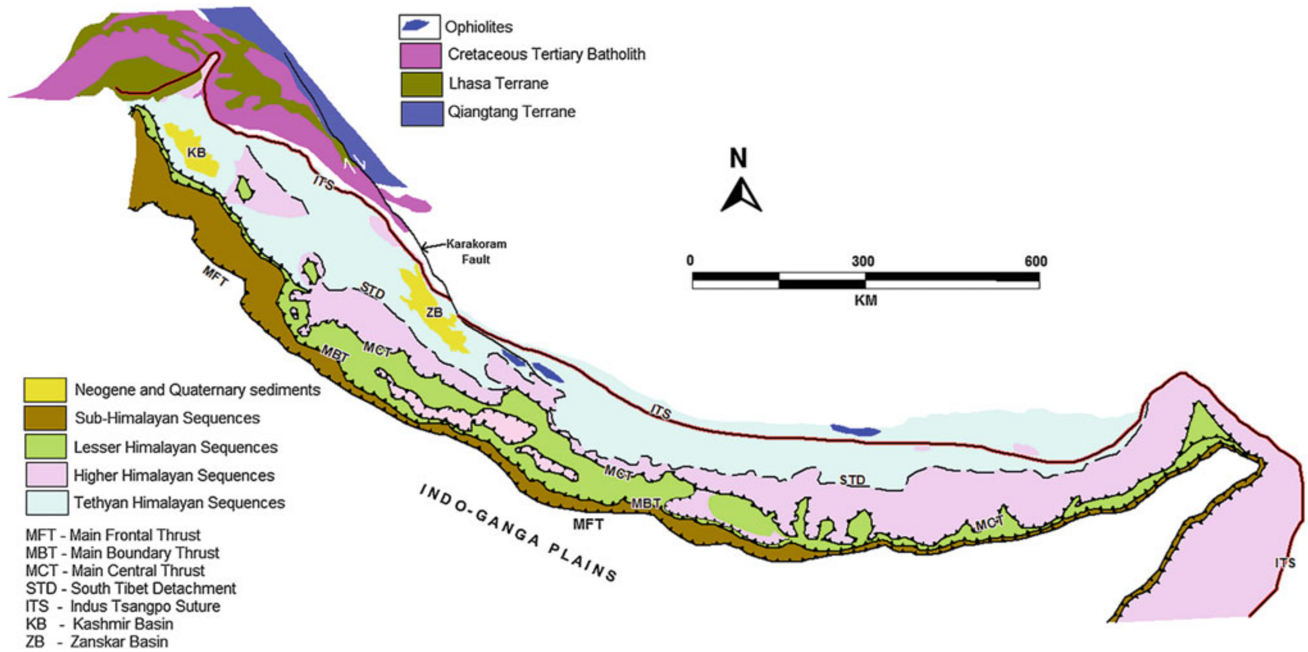

Fig. 10 Map showing geological subdivisions of the Himalaya (after Yin 2006; Valdiya 2010)

crystalline complex of the Higher Himalaya provides evidence of ductile deformation, intrusion and metamorphism at 2174, 1850, 500 Ma and in middle Miocene time. Between the Late Paleocene and the Early Oligocene, subduction of the Indian crust led to the formation of fold and thrust belt of the Tethyan Himalaya for which STD acted as the basal thrust. Continental sedimentation commenced only after mid-Oligocene time with the exhumation of the Higher Himalaya.

7 Cenozoic of Peninsular India

Restriction of Cenozoic records along the periphery of the Peninsula suggests that the craton remained elevated during this time period without any record of sedimentation. Onshore, basins in Gujarat mainland, Saurashtra, and Kachchh, Jaisalmer and Barmer basins of Rajasthan, carbonate succession of Niniyur Formation, Tamil Nadu and Baripada beds of Chhotanagpur Plateau constitute some of the best preserved Cenozoic records. In northeast India, the three important zones of Cenozoic sedimentation are (a) Shelf zone around Shillong-Mikir Plateau (b) Naga schuppen zone and (c) Kohima synclinorium and residual basins in Sylhet and Bengal. The fossiliferous Paleocene marine strata are recorded all along the West Indian shelf between Rajasthan and offshore Kerala and also in the East Indian shelf in the subsurface of West Bengal and outcrops in the South Shillong (Meghalaya) Front.

8 Quaternary

In India, several river valleys, coastal tracts and desert regions such as the Thar show well developed Quaternary sediments. The most important Quaternary fills occur in the valleys and extensive plains developed along the large river systems originating in the Himalaya i.e., the Indus, Ganga and Brahmaputra. These sediments have their provenance predominantly in the Himalaya.

Most of the river valleys in Peninsular India, both major and minor, contain late Quaternary strata with variable thicknesses. Significantly, a 74 Ka tephra layer commonly associated with the Youngest Toba Tephra (YTT) event has been identified in several river valleys in Peninsular India after being initially recorded in the Son-Narmada valleys. These river valley and floodplain sequences constitute an important archive for Quaternary palaeoclimatic studies and have served as recorders of variations in monsoonal strength and intensity that took place during the Late Quaternary in India. The wetter monsoonal phase corresponding to MIS 3 has been widely recognized in the river valley sediments.

The only Hominid fossil *Homo erectus narmadaensis* of the Indian subcontinent has been discovered from the conglomerates of the Narmada Valley (Sonakia 1984).

9 Epilogue and Summary

The trajectory of landscape and seascape evolution in the continents and oceans is to a large extent a function of geologic and tectonic evolution of the region. In continental landscapes, this trajectory is also influenced considerably by the nature of coupling between the geological and tectonic evolution with the climatic shifts at different time scales. The geology of the Indian subcontinent preserves an extensive record that spans more than 3.5 Ga beginning from the formation of early cratonic nuclei in the Archean and their evolution into a stable Peninsular landmass. The subsequent developments on which the geomorphological evolution was based are rooted in the rifting history of India that was initiated in the Late Palaeozoic and terminated in the end of Mesozoic. The rifting was also accompanied by two major episodes of volcanism, one of which, the 65 Ma Deccan volcanism, provided the basic relief structure on which geomorphological evolution proceeded from then onward in a large part of western and central India.

The final stages in the gross geomorphological evolution of the Indian region were largely determined by the processes connected with the northward movement of the Indian Plate and its subduction under the Eurasian Plate in the Cenozoic. These tectono-geomorphic processes resulted in the first order relief structure of the northern part of the Indian subcontinent with the progressive development of Himalayan topography from the Palaeocene onward as well as the isostasy driven evolution of a large subsiding area in front of the Himalaya due to lithospheric flexure.

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Past and the Present Climate of India

Ashok K. Singhvi and R. Krishnan

Abstract

The Indian monsoon, which comprises the seasonal reversal of winds and implies rainfall on land, is a complex system. Given that the national economy depends critically on monsoon, its rigorous understanding it warranted. We trace here the geological history of monsoon and the present trends of its performance. The monsoon as it is now is about 10–8 Ma old. It has fluctuated around a mean value at all timescales due to the response of causative factors to various global forcings—the dominant being the Sun-Earth geometry and consequent asymmetric heating of land versus oceans. Whereas most regions show analogous responses to global forcings, significant spatial heterogeneities are seen on shorter timescales. Instrumental data suggest general weakening of monsoon system and at the same time an increase in extreme events. A broad brush scenario of the monsoon and its variability through geological time is presented.

Keywords

Monsoon • Droughts • Floods • El Niño • Geological records • Proxies • Marine records • Long-term trends

1 Introduction

The climate of the Indian subcontinent is dominated by the monsoons which are pronounced seasonal reversals of winds and transitions from drier to wetter regimes. During the summers, the southwesterly winds pick moisture from the northern Indian Ocean and drop this on the landmass, providing the summer rainfall that is critical to the survival of the Indian society and its economy. The winter winds blow from the northeast regions of the Asian continent and travel towards the Indian Ocean. This annual cycle of atmospheric circulation arises from interactions of the seasonal changes in solar insolation with the land-ocean distribution such that variations in the thermal fluxes produce differential warming between the land and the sea, leading to development of convective cells and consequent moisture transport and deposition (i.e. rain), inland.

The food grain production of India has a proportional relationship to the monsoon, with its critical dependence on the onset, duration and distribution of rainfall and the periods of break monsoon conditions. While the present monsoonal conditions are tracked using variety of instruments, its past history is studied using geological archives. Studies on the monsoon using such geological archives and instrumental record have now established the following (Singhvi and Kale 2009; Singhvi et al. 2010, 2012):

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V. S. Kale (ed.), *Landscapes and Landforms of India*, World Geomorphological Landscapes,
DOI: 10.1007/978-94-017-8029-2_2,