International Journal of Humanities and Social Science Invention (IJHSSI)
ISSN (Online): 2319 – 7722, ISSN (Print): 2319 – 7714
www.ijhssi.org ||Volume 13 Issue 6||June. 2024 || PP.89-94

Exploring the Geological Development of the Indian Subcontinent

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ABSTRACT: *The geological development of the Indian subcontinent offers a comprehensive overview of the region's extensive and diverse geological history. This paper aims to elucidate the range of geological time periods represented within the subcontinent, highlighting notable rock formations such as lamprophyres, kimberlites, and carbonatites. Additionally, it delves into the pale biodiversity and pale biology, providing insights into the ancient life forms that once inhabited the terrain. Special emphasis is given to polar research and geophysics, reflecting the multidisciplinary nature of contemporary geological studies. The compilation is intended to serve as a valuable tool for geoscientists, researchers, and students, enhancing their understanding of the geological intricacies of the Indian subcontinent.*
Keywords: *Geophysics, Geological history, Indian subcontinent, Multidisciplinary geology*

Date of Submission: 20-06-2024 Date of Acceptance: 30-06-2024

I. INTRODUCTION:

The Indian subcontinent stands as one of the most geologically diverse and historically significant regions on Earth. Its geological timeline stretches from the ancient Hadean eon to the current geological epoch, encapsulating a vast array of geological events and formations. This remarkable diversity provides an extensive record of Earth's history, offering invaluable insights into the planet's geological processes [1].

The subcontinent's geology is marked by an extraordinary variety of rock types and mineral deposits. From the ancient, stable cratons in the southern parts to the geologically active and young Himalayan mountains in the north, the region showcases a broad spectrum of geological features. This diversity includes significant rock formations such as lamprophyres, kimberlites, and carbonatites, each contributing to the understanding of Earth's geological past.Early contributions to the field, such as Bose's pioneering description of carbonatite in 1884, highlight the long-standing interest and research in the geology of the Indian subcontinent. These early studies laid the groundwork for ongoing research and discoveries, illustrating the rich geoscientific heritage of the region.

In addition to its geological formations, the Indian subcontinent is a crucial area for studying paleobiodiversity and paleobiology. The fossil records found here provide a window into the life forms that once inhabited the region, enriching our understanding of Earth's biological history. Furthermore, modern studies have expanded to include polar research and geophysics, reflecting the interdisciplinary approach required to fully comprehend the subcontinent's geology.Compiling a comprehensive review of the Indian subcontinent's geology presents a formidable challenge due to the region's vast and intricate geological data. To address this, the Legacy Committee of the 36th International Geological Congress (IGC) selected forty-two pivotal topics that capture the essence of the subcontinent's geological narrative. These topics, now presented in this special issue of Episodes, have been meticulously reviewed and revised to provide a thorough and up-to-date account.

This compilation aims to serve as an essential resource for geoscientists, researchers, and students, offering a detailed exploration of the geological development of the Indian subcontinent. By examining the region's geological history and contemporary research, this collection highlights the subcontinent's significance in the broader context of global geology and underscores its role in advancing our understanding of Earth's dynamic systems.

THE INDIAN SUB-CONTINENT

The Indian Subcontinent is characterized by a complex mosaic of geological features, including Archean cratons, Proterozoic mobile belts, intracratonic sedimentary basins, and post-Cambrian cover sequences (Fig. 1). The major Archean cratons, such as Dharwar in the south, Bastar and Singhbhum in the east, Bundelkhand in the center, and Aravalli in the northwestern parts, are surrounded by mobile belts consisting of intensely deformed and metamorphosed supracrustal rocks. Notable mobile belts include the Southern Granulite belt adjacent to the Dharwar Craton, the Eastern Ghat Mobile Belt bordering the Dharwar, Singhbhum, and Bastar cratons, and the Aravalli-Delhi mobile belt associated with the Aravalli Craton. Additionally, the inter-cratonic Satpura mobile belt/Central Indian Tectonic Zone lies between the Singhbhum, Bastar, and Bundelkhand cratons.

The Himalayan Orogenic belt in the north, a Tertiary orogen overlying Precambrian basement, marks the northern boundary of the Indian subcontinent. Proterozoic sedimentary basins, historically referred to as 'Purana Basins,' are widespread across northwestern, north-central, east-central, and southern India, comprising extensive accumulations of virtually unmetamorphosed rock strata reaching up to 10,000 meters in thickness. Significant basins include the Marwar, Vindhyan, Chhattisgarh, Cuddapah, Bhima, and Kaladgi basins.

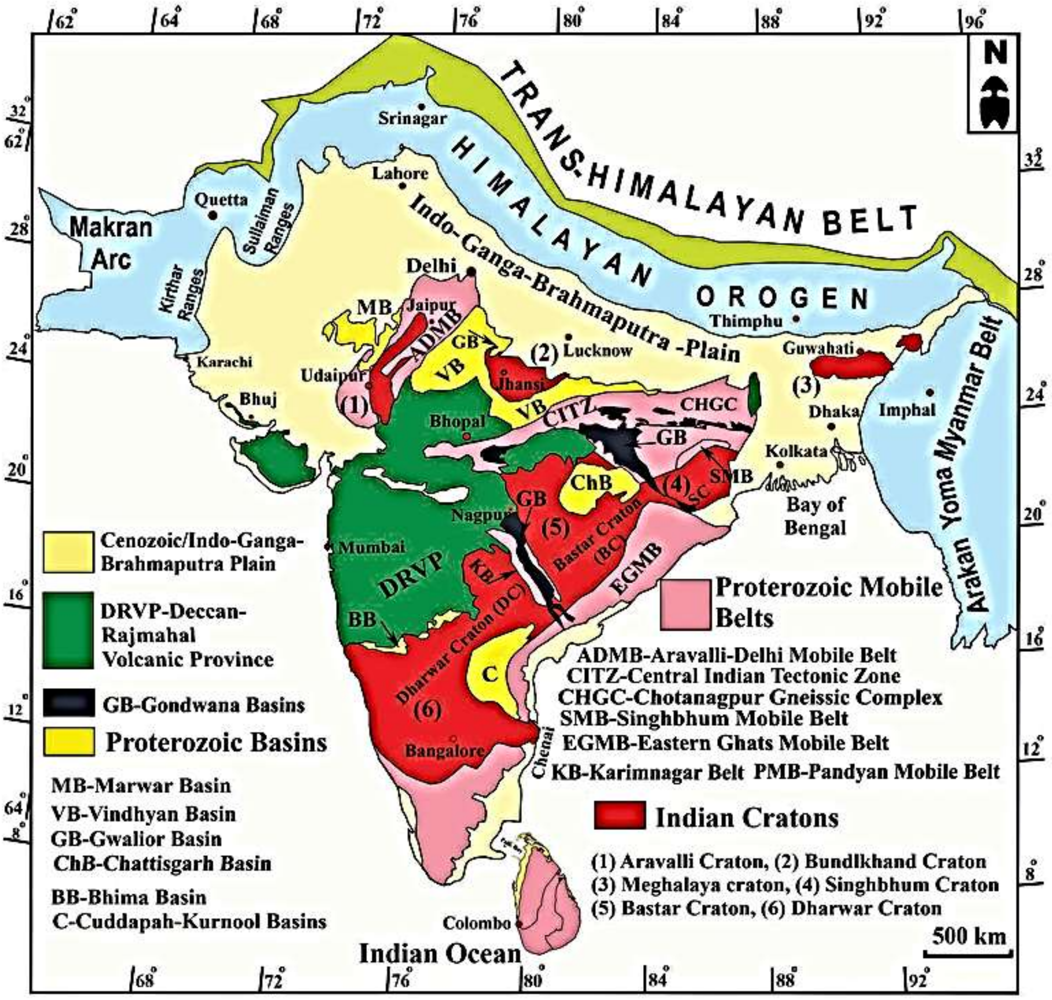

Fig 1. Geology and tectonics of the Indian Sub-continent

Post-Cambrian geological units in the subcontinent encompass diverse formations, such as the vast Deccan Volcanic Province in western and central India, the Rajmahal and Sylhet Traps in eastern India, coal-bearing Gondwana successions in Damodar, Satpura, Mahanadi, and Godavari rifts, Cretaceous marine sediments in the Narmada Valley, Tiruchirapalli (Cauvery Delta), and Meghalaya, as well as Coastal Tertiary and Quaternary sediments. Other notable features include Holocene (Recent) sediments along major river valleys, Tertiary and Quaternary sediments in the Himalayan foothills, the Indo-Gangetic and Brahmaputra plains (including the Bengal and Indus fans), extensive desert regions in northwestern India, and active volcanic centers in the Andaman Sea. The distribution of these diverse rock units across space and time underscores the geological complexity and significance of the Indian subcontinent. This special issue provides detailed insights into these tectonic domains, chronicling their evolution throughout geological history.

INDIA'S EARLY GEOLOGICAL RECORDS REVEALS ANCIENT CRUSTAL PROCESSES

The Indian terrain boasts several large Archean cratonic nuclei, pivotal for understanding Earth's early evolution and atmospheric development. However, research on the Hadean eon (4567-4030 Ma) is notably sparse. The differentiation of Earth's core and mantle likely occurred within ~30 million years of its formation [2, 3], inferred largely from short-lived isotopes due to the lack of preserved early terrestrial materials. Detrital zircon remains crucial for studying both the Hadean and Archean eons, providing insights despite challenges like metamorphic reworking. Advances in in situ measurement techniques, such as Laser-Ablation inductively coupled spectrometry (LA-ICPMS), secondary ion mass spectrometry (SIMS), and atom probe tomography, have significantly enhanced our ability to retrieve and interpret Hadean ages [4,5]

Researchers have utilized additional chemical indicators, such as Lu-Hf isotopes in zircon, to identify reworked sources in zircons extracted from orthogneisses [6]. Some of the earliest known reports of >4.0 billion-year-old zircons, including those from the Acasta Gneiss in Canada [7], the Itsaq Gneiss in Greenland [8] the North China Craton [9], and Tibet have drawn significant attention. Particularly notable are reports from the Yilgarn Craton in Australia, dating back to ~3.0 billion years, found in metasedimentary units which have been extensively studied [10].

Hadean-age zircons from the Indian subcontinent have been sporadically reported [11, 12]. Eoarchaean-detrital zircon reports [13] from the Singhbhum Craton have utilized coupled isotopic data to examine mantle reservoir characteristics during early crustal accretion on Earth. researchers combined Zircon U-Pb and Lu-Hf data to suggest remnants of Neohadean continental crust in the Coorg block of the southwestern Dharwar Craton.While current research predominantly focuses on Paleoarchean and younger geological events, this section reviews and critically analyzes the evolutionary theories of the Dharwar, Singhbhum, and Bundelkhand cratons, providing a comprehensive overview of their current understanding.

PROTEROZOIC TECTONIC ZONES

Proterozoic Tectonic Zones refer to geological regions formed during the Proterozoic eon (approximately 2.5 billion to 541 million years ago) characterized by significant tectonic activity, deformation, and metamorphism. These belts are typically located at the boundaries of cratons (stable, ancient parts of the Earth's crust) and represent zones where the crust has been reworked due to plate tectonic processes such as continental collision, subduction, and rifting. Mobile belts are crucial in understanding the tectonic evolution of continents and the assembly of supercontinents throughout geological history.

This section updates four key mobile belts surrounding major cratons of the Indian peninsula. Researcher discusses the Southern Granulite Terrane (SGT), highlighting its mosaic of crustal blocks and evidence of multiple supercontinent cycles. Dasgupta [14] reviews the Eastern Ghats Belt (EGB), linking it to the Prydz Bay region of East Antarctica and showing signatures of the Columbia and Rodinia supercontinents. Chattopadhyay et. al. [15] explore the Central Indian Tectonic Zone (CITZ), detailing its role in merging the northern and southern Indian cratons and preserving evidence of supercontinent cycles. Fareeduddin [16] describe the Aravalli-Delhi Mobile Belt (ADMB), suggesting an ancient protocontinent's survival through various orogenic events. These studies collectively underscore the belts' involvement in supercontinent formations and their implications for the Proterozoic evolution of the Indian landmass.

PROTEROZOIC SEDIMENTARY BASINS

Proterozoic Sedimentary Basins are large, stable, and relatively undeformed regions of the Earth's crust that formed during the Proterozoic Eon (approximately 2.5 billion to 541 million years ago). These basins are characterized by thick sequences of sedimentary rocks that accumulated in depressions or low-lying areas within cratons, which are the ancient and stable parts of the continental lithosphere. Proterozoic cratonic basins are important for studying the geological history of the Earth, including sedimentation processes, basin evolution, and the history of the Earth's atmosphere and biosphere. They often contain valuable resources such as minerals, oil, and gas.

The ~3.0 billion-year Precambrian history of the Indian subcontinent involves craton stabilization through granitoid emplacement, polyphase orogenic belt formation, and the development of sedimentary basins. The role of Indian cratons in supercontinent cycles remains debated, with recent studies linking pericratonic sedimentary basins to the assembly and breakup of supercontinents like Columbia and Rodinia. Patranabis-Deb and Saha summarize Proterozoic basin data in this context.Additionally, two key Precambrian sedimentology topics are microbial influences on sedimentation and the oxygenation of the atmosphere and hydrosphere. Indian cratonic basins contain rich Microbial mat Induced Sedimentary Structures (MISS). Sarkar et al. [17] review these features, while Chakraborty et al. discuss oxygenation history evidence, suggesting the deep ocean was largely anoxic during much of the Proterozoic [18].

PROTEROZOIC VOLCANIC AND PLUTONIC EVENTS

The geological processes involving the generation, movement, and crystallization of magma during the Proterozoic Eon, which spans from approximately 2.5 billion to 541 million years ago. These events include the intrusion of magma into the Earth's crust, forming large bodies of igneous rock known as plutons, and the eruption of magma onto the surface, creating volcanic rocks and structures. Proterozoic magmatic activity occurred in various tectonic settings, such as rift zones, subduction zones, and continental collision zones, and played a key role in the formation and modification of the Earth's crust. These magmatic events also contributed to the creation of significant mineral deposits, including ores of nickel, copper, platinum, and gold. Understanding Proterozoic magmatic events is essential for reconstructing the Earth's geological history, particularly the processes involved in the assembly and breakup of ancient supercontinents like Columbia and Rodinia, and for exploring the distribution of valuable mineral resources formed during this era.

The main objective of this section is to present an overview of Proterozoic magmatism in India through a series of thematic reviews. The section includes four papers covering various aspects of Proterozoic magmatic events such as mafic, silicic, carbonatite-alkaline, and lamprophyre-kimberlite magmatism. Radhakrishna and Vijaya Kumar [19] identify several discrete Paleoproterozoic mafic magmatic events in the Indian Shield using U-Pb ages and paleomagnetic data, emphasizing their fractional crystallization from sub-continental lithospheric mantle-derived magmas likely influenced by mantle plumes. Santosh Kumar et al review Proterozoic felsic and mafic magmatism across India, including the Himalayas, discussing their implications for crustal evolution in volcanic and plutonic environments. Chalapathi Rao et al [20] provide an overview of lamprophyres, discussing their types and associations with kimberlites, suggesting various geological processes responsible for their formation. Paul et al [21] review Proterozoic alkaline rocks and carbonatites in Peninsular India, highlighting distinct phases of magmatism and their geological significance in the context of continental rifting and collisional processes during the Wilson cycle.

THE FORMATION OF THE HIMALAYAN MOUNTAINS

This youthful and dynamic mountain range provides a distinctive chance to study the geological processes of mountain building across different structural tiers. Alongside extensive tectonic activities, the region exhibits a spectrum of sedimentary processes from marine to terrestrial environments, the evolution of foreland basins, typical magmatism associated with convergent margins, and metamorphic rocks that serve as records of the transport of shallow materials to deeper crustal and mantle depths. Furthermore, the fossil records found in these rocks offer insights into the evolution of organisms over time in the Himalayan orogen.

Thakur et al. [22] linked the formation of the Kangra Basin to the reactivation of the Jawalamukhi Thrust (JT) in the NW Himalaya, where high precipitation and microseismicity in the eastern Dhauladhar Range facilitated basin development, unlike the drier western part. The basin's sedimentation primarily derives from erosion of the Dhauladhar Range, influenced by the JT's foreland propagation. OSL dating on basin sediments and terrace surfaces indicates late Quaternary JT reactivation, synchronizing with Kangra Basin formation.

Jain et al. [23] observed the juxtaposition of terranes across the Main Central Thrust Zone (MCTZ), highlighting the Inner Lesser Himalayan (iLH) sedimentary belt's U-Pb detrital zircon ages (2.05-1.80 Ga), suggesting sourcing from the ~1.9 Ga magmatic arc and the Archean Aravalli-Bundelkhand Indian craton. In contrast, the Great Himalayan Sequence (GHS) along the MCT shows Neoproterozoic (1.05-0.85 Ga) detrital zircon, and the Tethyan Himalayan Sequence (THS) exhibits early Paleozoic zircon. Singh documented diverse magmatic episodes in the Himalayas from the Paleoproterozoic to the present, correlating peaks with supercontinent amalgamation and breakup events: Columbia/Nuna (Paleoproterozoic), Rodinia (Neoproterozoic), Gondwanian (Cambro-Ordovician), Pangea (Permian), and Himalayan (Cretaceous to Tertiary). This orogenesis includes subduction-related and collisional magmatism processes.

PALAEOBIODIVERSITY AND PALAEOBIOLOGY OF THE INDIAN SUBCONTINENT

The Indian subcontinent, once part of Gondwanaland, drifted northward independently over millennia before colliding with Asia, forming the Himalayan mountain chain. Fossil discoveries across different geological periods from the Himalayas and peninsular India provide valuable insights into Cambrian biozonation, vertebrate diversity, evolution, and intercontinental relationships prior to India's separation from Gondwanaland. Studies also highlight the development of lignite deposits along India's western margin and discuss the biogeographic links during its northward journey, revealing complex evolutionary patterns and dispersals of life forms across the region.

Prior to its collision with Asia, the Indian plate, situated in an equatorial belt, hosted lignite deposits along its western margin in Gujarat and Rajasthan. These deposits are rich sources of terrestrial and marine fossils, including vertebrates, invertebrates, and plants. Vandana Prasad et al. documented a diverse collection of dinoflagellate cysts from the Akli Formation exposed in the Giral Lignite Mine, Bamer (Rajasthan). Based on dinoflagellate biozonation, they suggest a Danian-Thanetian (Palaeocene) age for the Akli Formation, making it the oldest lignite deposit on India's western margin compared to deposits in Cambay, Kutch, and other regions [24].

Additionally, the drifting Indian plate has been identified as a center of origin for various mammalian groups such as Primates, Perissodactyla, and Artiodactyla. Sunil Bajpai and V.V. Kapur discuss recent fossil discoveries from the Early Eocene of India, a period marked by receding Neotethys, India's collision with Asia, and greenhouse conditions on Earth. They highlight significant Early Eocene mammalian clades found in Indo-Pakistan, shedding light on their biogeographic origins, evolutionary radiation, and dispersal patterns. The authors support the Out-of-India dispersal hypothesis, suggesting that certain mammalian groups, including whales and perissodactyls, originated in the Indian subcontinent before dispersing to other continents.

RECENT ADVANCES IN ANTARCTIC AND OCEAN RESEARCH

Antarctica, the Indian subcontinent, and the adjacent oceans play crucial roles in understanding the evolution of supercontinents like Rodinia and Gondwana, the opening of the Indian Ocean, and the development of India's eastern and western continental margins. Recent studies have illuminated these areas but also raised challenges such as differences in breakup processes along Antarctic margins, defining continent-ocean boundaries, and understanding magmatic bodies in East Antarctica [25]. Additionally, Antarctica's influence on the global climate system, including its interaction with the Asian monsoon, remains a topic of significant research. This section explores Indian contributions to Antarctic geoscience, encompassing geological histories, paleoclimatic records, and structural features of the Indian continental margin and adjacent ocean basins.

The continental margins of India, shaped by Gondwanaland breakup, India's northward drift, and Himalayan formation, feature diverse geological structures like aseismic ridges, submarine plateaus, and seamounts [26]. Yatheesh's paper reviews these features, their evolution, and unresolved questions such as continent-ocean boundaries, basin formation timing, crustal configurations, and seismic activity in areas like the Chagos Bank of the Laccadive-Chagos Ridge.

II. CONCLUSION

The collection of papers presented in this compilation spans a diverse array of geological topics encompassing the Indian subcontinent. From the exploration of ancient rocks like lamprophyres, kimberlites, and carbonatites to detailed investigations into paleobiodiversity and paleobiology, this volume reflects the rich geological heritage of the region. special sections dedicated to Polar research and Geophysics add depth and breadth to our understanding, highlighting the interconnectedness of global geosciences with local phenomena. The collaborative effort of ten section editors and nearly one hundred authors underscores the depth of expertise and the collective endeavor within the geoscientific community.This compilation serves not only as a snapshot of current research but also as a resource enriched with updated references, offering insights and frameworks for future investigations. It is our hope that these contributions will inspire further exploration and understanding of the geological complexities of the Indian subcontinent, contributing to broader scientific discourse and societal knowledge.

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