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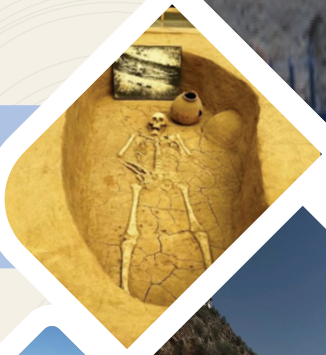
XXII INQUA INDIA 2027

FIELD GUIDE

INPOST - 03

QUATERNARY LANDSCAPE EVOLUTION, GEOARCHAEOLOGY AND SALINE BASIN DEVELOPMENT IN NORTHWESTERN INDIA: A FIELD EXCURSION TO RAKHIGARHI, KALIBANGAN AND SAMBHAR LAKE

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विज्ञान एवं प्रौद्योगिकी विभाग के अंतर्गत स्वायत्त संस्थान, भारत सरकार
An autonomous institute under the Department of Science and Technology, Government of India
1946

विज्ञान एवं प्रौद्योगिकी मंत्रालय MINISTRY OF SCIENCE AND TECHNOLOGY
सत्यमेव जयते
पृथ्वी विज्ञान मंत्रालय Ministry of Earth Sciences
सत्यमेव जयते
1946
NCPOR
INQUA International Union for Quaternary Research
ASSOCIATION OF QUATERNARY RESEARCHERS

Published in 2026 by

XXII INQUA Congress, India
Birbal Sahni Institute of Palaeosciences (BSIP)
53, University Road
Lucknow – 226007, Uttar Pradesh
India

Website: www.inquaindia2027.in
Email: inqua.india@bsip.res.in

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Published under the overall supervision of:
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Compilation and editing: Field Trips Committee in collaboration with the INQUA 2027 Secretariat.

Design and Production:
XXII INQUA Congress 2027
Anupam Sharma, BSIP, Lucknow
Akhilesh K Yadava, BSIP, Lucknow
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Creative Team, Expression 360, New Delhi

INQUA INDIA 2027

Field Guide Book

INPOST-03

Quaternary Landscape Evolution, Geoarchaeology and Saline Basin Development in Northwestern India: A Field Excursion to Rakhigarhi, Kalibangan and Sambhar Lake

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Team Leaders



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Bharti Sharma is a geologist, geoscience entrepreneur, and founder of AADYA – Planetary and Geoscience Research, working at the intersection of Earth and planetary science, geomorphology, geoheritage, and geospatial research. She holds a B.Sc. in Geology from Amity University Haryana and an M.Sc. in Geology from Doon University, and is pursuing a PG Diploma in Remote Sensing and GIS at IIRS, ISRO. Her field experience spans the Himalayas, Thar Desert, Deccan Traps, Australia, and Utah, USA, as an analogue astronaut. Her interests include geoheritage assessment and conservation, planetary analogues, geomorphological mapping, and communicating geological landscapes as archives of environmental change



Dr. Ravindra Pratap Singh
Eminent Geoscientist and Associate Professor
Earth and Planetary Sciences at the University of Allahabad,
Prayagraj.

Dr. Ravindra Pratap Singh is an eminent geoscientist and Associate Professor in the Department of Earth and Planetary Sciences at the University of Allahabad, Prayagraj. A dedicated scholar and academician, Dr. Singh has been a cornerstone of the department's teaching and research faculty since 2016. Prior to his appointment at the University of Allahabad, he served with distinction on the faculty of the University of Delhi from 2011 to 2016, contributing significantly to undergraduate and postgraduate geoscientific education. His scholarly research synthesizes engineering geology, environmental geology, tectono-geomorphology, and slope stability analysis, integrating advanced geophysical methods and Geographic Information Systems (GIS). Focusing predominantly on the fragile Himalayan terrain, Dr. Singh's empirical investigations address landslide dynamics, natural hazard risk mitigation, and active tectonics. His primary research endeavors encompass Quaternary landscape evolution, the identification and preservation of national geoheritage sites, and the sustainable promotion of geotourism across sensitive geomorphic corridors. Recognized internationally for his scientific contributions, Dr. Singh holds professional membership in the International Association of Hydrological Sciences (IAHS). In his capacity as a co-leader for the XXII INQUA Congress field excursion, he contributes his extensive academic expertise to showcasing India's dynamic Quaternary landscapes and tectonic heritage to the global scientific community.



Kumar Gaurav
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Kumar Gaurav is currently working as an Assistant Professor at Government Engineering College, Nawada, Bihar. Primarily engaged in teaching Engineering Geology. He hold an M.Sc. in Geology from Banaras Hindu University and an M.Tech. in Geoexploration from IIT Bombay. His academic and professional journey integrates Engineering Geology, Geoexploration, Remote Sensing, GIS, and Applied Geosciences. He has contributed to diverse projects involving geospatial analysis, natural-resource assessment, and geo-archaeological investigations, applying geological and Earth observation techniques to understand archaeological landscapes. His interests include engineering geological investigations, rock characterization, geological mapping, remote sensing, GIS, and interdisciplinary applications of geoscience for infrastructure, heritage conservation, and sustainable development.



Dr. Pradeep Mawar
Director (Retd.)
Geological Survey of India (GSI),

Dr. Pradeep Mawar, Director (Retd.), Geological Survey of India (GSI), is a veteran geoscientist with a distinguished 34-year career in national geoscientific research, regional mapping, and institutional leadership. Having superannuated from GSI's Northern Region headquarters in Lucknow, his scientific expertise encompasses the petrology, stratigraphy, and regional geology of Northern and Himalayan India. Throughout his tenure with the Geological Survey of India, Shri Mawar led crucial geological investigations, most notably the systematic mapping and thematic compilation of granite occurrences across Jammu & Kashmir and Uttar Pradesh. Between 2005 and 2009, he served on India's National Working Group for the UNESCO/IUGS International Geoscience Programme (IGCP-510: A-Type Granites through Earth History), representing GSI in international technical sessions and field workshops. Building upon more than three decades of field leadership, Shri Mawar remains actively engaged in Quaternary landscape evolution, geoheritage conservation, and geotourism. As a co-leader for the XXII INQUA Congress field excursion, he contributes his extensive field expertise to the scientific interpretation of dynamic Quaternary depressions and historic river corridors for the global geoscientific community.



Dr. Ravi Kumar Vendavulla
Director (Retd.)
Geological Survey of India (GSI),

Dr. Ravi Kumar Vundavalli, Director (Retd.), Geological Survey of India (GSI), is an eminent geoscientist with over three decades (1974–2008) of distinguished service across terrestrial, Himalayan, and marine oceanographic domains. During his tenure at GSI, Shri Vundavalli participated in the high-altitude Zemu Glacier expedition in North Sikkim, carried out systematic geological mapping of Koraput district, and evaluated the Panchpatmali bauxite deposit—which laid the foundation for NALCO's Alumina Plant. In the Marine Geology Wing, he executed offshore placer mineral investigations, mapped India's Exclusive Economic Zone (EEZ), and evaluated polymetallic nodules in the Central Indian Ocean Basin. Following his superannuation, Shri Vundavalli pioneered Open Source GIS (FOSS4G) and Societal-GIS in India, serving on the OSGeo International Board of Directors (2010–2011) and conducting over a hundred capacity-building workshops nationwide. He also mentored DST-sponsored community spatial projects, including Mana Rajahmundry. Currently, Shri Vundavalli champions national Geoheritage and Geotourism initiatives, conceptualizing Indian Geopark circuits across regional corridors such as Godavari, Hyderabad, Vizag, and Chitradurga. His ongoing scientific research focuses on Quaternary landscape evolution, geomorphological assessments, and co-leading field excursions along the Godavari river corridor and coastal Andhra Pradesh.



Ms. Sandhya Sharma
Assistant Professor
School of Law, SGT University, Gurugram

Ms. Sandhya Sharma is an Assistant Professor at the School of Law, SGT University, Gurugram, with a legal background and an emerging interdisciplinary research profile at the intersection of law, geoheritage and archaeology. She is currently pursuing doctoral research examining the legal and policy dimensions of geoheritage and its conservation. Her research interests extend to geoarchaeology, archaeological landscapes, heritage governance, environmental regulation, and the protection of sites where geological processes and human histories converge. Her work seeks to understand how legal and policy frameworks can support responsible conservation of geological and archaeological heritage while enabling sustainable engagement with landscapes, communities and cultural histories.



Ms. Veenita Rani
GIS Research Analyst
Mehar Geospatial Solutions.

Ms. Veenita Rani serves as a GIS Research Analyst at Mehar Geospatial Solutions. She holds degrees in Geography from Chaudhary Charan Singh University, an M.Sc. in Geospatial Science and Technology from Delhi Technological University, and a PG Diploma in Remote Sensing and GIS (Urban & Regional Planning) from IIRS-ISRO, Dehradun.

Her research experience includes roles at the Wildlife Institute of India and the Govind Ballabh Pant National Institute of Himalayan Environment, focusing on climate vulnerability, biodiversity, and forest resources. Expanding into archaeology, Veenita applies remote sensing, GIS, and satellite data to identify, map, monitor, and conserve historical landscapes and cultural heritage.

Abstract

The field excursion examines three geologically significant sites in northwestern India—Rakhigarhi (Haryana), Kalibangan (Rajasthan), and Sambhar Lake (Rajasthan)—to investigate the relationships between Quaternary landscape evolution, climate variability, human settlement, and saline basin development.

At Rakhigarhi and Kalibangan, the principal geological issues are the role of paleochannels, floodplain evolution, groundwater availability, and monsoon variability in influencing the development, sustainability, and transformation of Harappan settlements. Particular attention will be given to geoarchaeological evidence of river migration, paleohydrology, sediment provenance, and human adaptation to changing environmental conditions during the Holocene.

At Sambhar Lake, the excursion will explore the tectonic origin of the basin, Quaternary climatic controls on lake evolution, evaporite sedimentation, and aeolian modification of the playa system. The site also provides an opportunity to examine modern hypersaline environments as terrestrial analogs for evaporitic paleolake basins on Mars.

Collectively, the field transect addresses how tectonics, climate, hydrology, and geomorphic processes interact to shape both natural landscapes and long-term human occupation in the arid and semi-arid regions of northwestern India.

Preamble

Northwestern India preserves one of the most remarkable records of the interactions between climate, landscape evolution, water resources, and human societies. Across the semi-arid plains of Haryana and Rajasthan, Quaternary environmental changes have influenced river systems, groundwater availability, saline lake development, and human occupation patterns for thousands of years. Therefore, the region provides an exceptional natural laboratory for investigating the links between geological processes and cultural history.

This field excursion traverses three contrasting but interconnected sites: the Rakhigarhi, Kalibangan, and Sambhar Lake. Together, these locations record different expressions of landscape evolution in the Holocene. Rakhigarhi and Kalibangan offer opportunities to examine geoarchaeological evidence from major Harappan settlements situated within paleochannel dominated environments, where changing hydrological conditions influenced settlement development and their long-term resilience. Sambhar Lake provides a contrasting endorheic basin system where tectonic activity, climatic variability, evaporite sedimentation, and aeolian processes have shaped the evolution of India's largest inland saline lake.

The excursion integrates geology, geomorphology, archaeology, paleoclimate, and geoheritage to explore how environmental systems have evolved over time and how human communities have adapted to changing water availability. In addition, Sambhar Lake offers a modern analogue for evaporitic paleolake environments of planetary interest, extending the relevance of the field transect beyond Earth to comparative planetary geology and astrobiology.

Through field observations, discussions, and examinations of key geological and archaeological features, participants will gain an interdisciplinary perspective on landscape evolution and human– environment interactions in one of South Asia's most significant Quaternary regions.

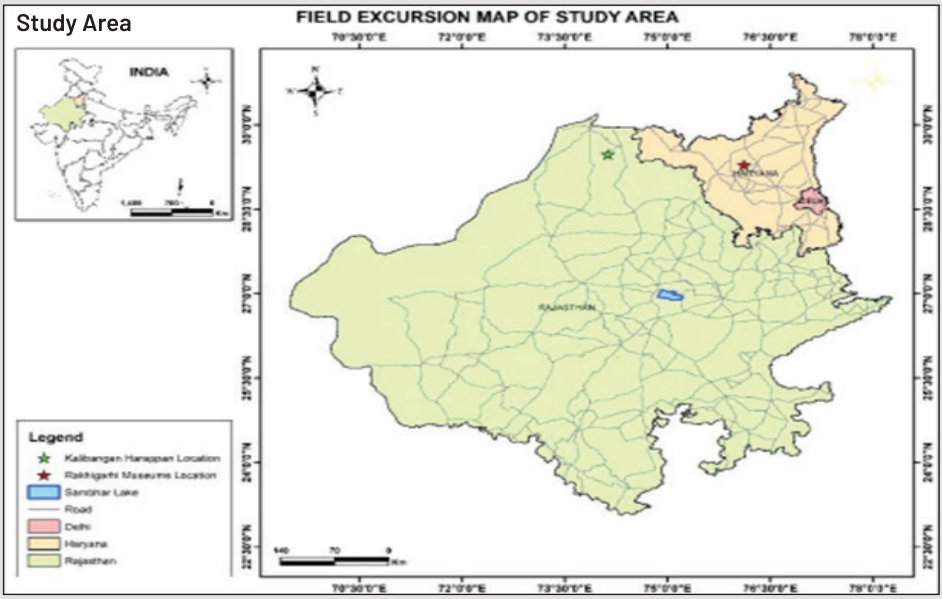


Figure 1:- Study Area Map of Rakhigarhi, Kalibangan and Sambhar Lake.

Research Problem as it Stands Globally and How the Field Transect is Unique in Context

Understanding the interactions between climate variability, hydrological systems, landscape evolution, and human societies remains a major challenge in Quaternary science and geoarchaeology. Researchers worldwide are seeking to determine how changes in precipitation, river behavior, groundwater availability, and tectonic activity influence ecosystem development, settlement sustainability, and long-term environmental resilience in arid and semi-arid regions. Similar questions are being actively investigated in the Nile Valley, Mesopotamia, Central Asia, the American Southwest, and other dryland regions where ancient civilizations depended on highly sensitive water systems.

In northwestern India, these questions are particularly important because the region preserves a unique record of Holocene climatic fluctuations, paleochannel evolution, Harappan urbanization and saline lake development. Despite decades of research, significant debates remain regarding the hydrological conditions that supported major Harappan settlements, the role of monsoon variability in settlement reorganization, and the influence of river migration on the long-term landscape stability.

The field transect presented here is unique because it integrates three complementary archives of environmental changes. Rakhigarhi records human adaptation to a paleochannel-dominated alluvial landscape. Kalibangan preserves evidence of settlement development along a large inherited fluvial corridor, whose hydrological history remains a subject of active investigation. Sambhar Lake provides an independent climatic and tectonic archive through its evaporite sequences, playa geomorphology, and saline hydrology. Together, these sites allow participants to examine the coupled effects of climate, water availability, geomorphic processes, and human responses within a single regional framework.

Beyond terrestrial applications, Sambhar Lake also provides an opportunity to explore the use of hypersaline playa environments as analogs for evaporitic paleolake systems on Mars, linking regional field observations to broader questions in planetary geology and astrobiology.

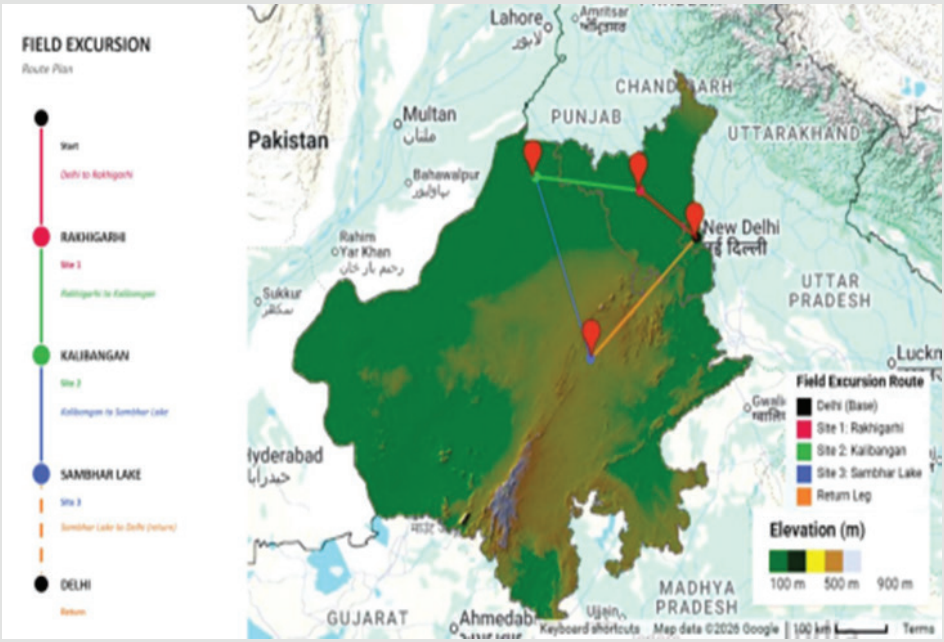


Figure 2:- Transect Map of the study area

Field Transect and Excursion Overview

Day	Route	Distance	Key Activities
Day 1- 9 Feb	Delhi - Rakhigarhi Hanumangarh	~470 km	Travel; visit the Rakhigarhi archaeological site; introduction to the Ghaggar alluvial plain and Harappan geoarchaeology.
Day 2- 10 Feb	Hanumangarh - Kalibangan - Hanumangarh	~60 km	Kalibangan excavations, Ghaggar paleochannel, archaeological stratigraphy, erosional exposures, museum visit.
Day 3- 11 Feb	Hanumangarh - Sambhar Lake	~340 km	Travel across the Thar margin: Introduction to Sambhar Basin geomorphology and Quaternary evolution.

Day 4- 12 Feb	Sambhar Lake	~40 km field traverse	Basement rocks at Shakambhari Hill; quartzites and quartz veins; salt pans; evaporite processes; and basin evolution
Day 5- 13 Feb	Sambhar Lake-Delhi	~300 km	Field synthesis; discussion on tectonics, paleoclimate, geoarchaeology, and geoheritage; return to Delhi

Regional Geology of Rakhigarhi

Geological Setting

Rakhigarhi is situated in the Hisar district of Haryana within the northwestern sector of the Indo Gangetic Foreland Basin. The region is characterized by extensive Quaternary alluvial deposits derived from the Himalayan and Sub-Himalayan river systems. The present landscape consists of low-relief alluvial plains, abandoned channel belts, interfluves, and aeolian-modified surfaces that record repeated phases of fluvial activity and climatic change during the Late Quaternary and the Holocene.

Field observations during the excursion were limited to exposed archaeological excavations within the settlement mounds. The excavated areas revealed mud-brick architectural remains, habitation surfaces, and cultural deposits representing successive phases of Harappan occupation. These exposures document the archaeological stratigraphy of the site, whereas the underlying Quaternary alluvial sediments and inferred paleochannel deposits discussed in the literature remain concealed beneath this archaeological sequence.

Stratigraphy

The subsurface geology is dominated by unconsolidated Quaternary sediments, comprising channel sands, overbank silts, floodplain clays, and localized aeolian deposits. Geophysical investigations and borehole data from the Ghaggar–Chautang region reveal thick sand bodies interpreted as buried paleochannel deposits. These sandy units are overlain by finer-grained floodplain sediments and represent former river courses that played an important role in groundwater storage and recharging.

Structural Framework

Rakhigarhi occupies the tectonically stable Sutlej-Yamuna interfluve of the northwestern Indo Gangetic foreland basin. The long-term tectonic subsidence of the foreland basin has created accommodation space for the thick Quaternary alluvial succession that underlies the site. River avulsion in this region is partly controlled by subtle tectonic tilting of the

foreland surface (Singh et al., 2017; Khan et al., 2019), which has influenced the repeated migration of Himalayan-fed river courses across the interfluve throughout the Holocene. Although no active fault structures are exposed at Rakhigarhi, Neotectonic tilting of the landscape is a contributing mechanism to the drainage reorganization that shaped the site's hydrological setting.

Quaternary Geology and Paleoenvironment

The Quaternary history of the region is closely linked to fluctuations in the Indian Summer Monsoon and changes in river dynamics. Sedimentological, geochronological, and geophysical studies indicate that large Himalayan-fed river systems occupied parts of the Ghaggar-Hakra region during the earlier phases of the Late Pleistocene and Early Holocene. However, by the time of the Mature Harappan occupation, the landscape around Rakhigarhi was dominated primarily by monsoon-fed fluvial systems, relict paleochannels, floodplain environments, and groundwater bearing alluvial deposits.

These environmental conditions created a favorable setting for long-term human occupation by providing fertile soils, seasonal surface water, groundwater resources, and relatively stable terrain that is suitable for agriculture and settlement development. Consequently, Rakhigarhi represents an important geoarchaeological archive for understanding the interaction between Holocene environmental change and the evolution of the Indus civilization in northwestern India.

Flora, Fauna and Climate of Rakhigarhi

Rakhigarhi lies within the semi-arid plains of northwestern Haryana and experiences a hot semi arid (BSh) climate according to the Köppen-Geiger classification. The region receives approximately 450–500 mm of annual rainfall, with nearly 80% of it falling during the southwest monsoon between July and September. Summers are extremely hot, with temperatures frequently exceeding 45°C, whereas winters are cool and dry, with January temperatures occasionally approaching freezing during cold-wave conditions.

Natural vegetation is dominated by drought-tolerant thorn-scrub and dry deciduous species typical of the northwestern Indo-Gangetic plains. Common trees include khejri (Prosopis cineraria), babool (Vachellia nilotica), neem (Azadirachta indica), and ber (Ziziphus mauritiana). The agricultural landscapes surrounding the archaeological site support wheat, mustard, pearl millet, cotton, and fodder crops cultivation.

The region supports a variety of birds, reptiles, and small mammals that are adapted to semi-arid environments. Seasonal wetlands and irrigation channels provide temporary habitats for migratory and resident bird species in the region. The modern climate reflects the strong dependence of local hydrology and agriculture on monsoonal precipitation, a relationship that has likely influenced human settlement patterns in the region since the start of the Holocene.

Literature Review

Rakhigarhi is one of the largest known urban centers of the Indus Civilization and has become a focal point for interdisciplinary research integrating archaeology, geomorphology, paleohydrology, geophysics, and paleoclimate studies. Early archaeological investigations established the site's importance through evidence of urban planning, craft production, burial practices, and long-term occupation, spanning the Early, Mature, and Late Harappan periods. More recent geoarchaeological studies have shifted attention toward understanding the environmental settings that supported the growth and persistence of settlements.

Research over the last two decades has demonstrated that Rakhigarhi occupied a landscape dominated by Quaternary alluvial deposits and paleochannelsystems associated with the Ghaggar– Chautang drainage network. Geoelectrical surveys and remote-sensing investigations have identified extensively buried channel sands beneath the surrounding plains, suggesting the presence of significant groundwater reservoirs that may have sustained settlement and agriculture. Settlement distribution analyses further indicate that many Harappan sites in Haryana preferentially occupied paleochannel corridors and floodplain environments where water availability and fertile soils were concentrated.

One of the most important developments in recent research is the hydrological history of northwestern India. Earlier hypotheses proposed that Harappan settlements flourished along a large, glacier-fed Himalayan River, commonly associated with the Saraswati tradition. However, geochronological, provenance, and sedimentological studies now indicate that major Himalayan fed channels largely shifted away from the region before the Mature Harappan period. Consequently, the prevailing interpretation is that Rakhigarhi relied primarily on monsoon-fed rivers, floodplain groundwater, paleochannel aquifers, and locally managed water storage systems rather than on a large perennial glacier-fed river.

Paleoclimate studies have further demonstrated that strengthened Indian Summer Monsoon conditions during the mid-Holocene coincided with the expansion of Harappan settlements across Haryana and adjacent regions. Subsequent weakening of the monsoon after approximately 4.2 ka BP likely altered water availability and contributed to broader settlement reorganization across the Indus region. Nevertheless, evidence from Rakhigarhi suggests that environmental change did not result in immediate abandonment but rather in adaptive responses and gradual transformation of settlement patterns.

Outstanding Research Issues

Despite these significant advances, several important questions remain unresolved.

1. Local Water Sources: The relative contributions of seasonal river flow, groundwater stored in paleochannel sands, rainfall, and artificial water-storage systems remain poorly quantified.

2. Paleochannel Chronology: The precise timing of river migration, channel abandonment, and groundwater recharge phases around Rakhigarhi requires additional high-resolution geochronological studies.

3. Human–Environment Interactions: The mechanisms through which Harappan populations adapted to changing hydroclimatic conditions remain poorly understood.

4. Groundwater Reconstruction: Direct reconstruction of ancient groundwater levels and aquifer behavior during the Early, Mature, and Late Harappan phases remains limited.

5. Integrated Geoarchaeological Models: Future studies should combine archaeology, sedimentology, geophysics, geochemistry, and paleoclimate data to develop site-specific models of settlement sustainability and environmental resilience.

Therefore, Rakhigarhi remains one of the most important laboratories for investigating the relationship between water availability, environmental change, and urban development in the Indus Civilization.

Rakhigarhi: Location Description (Geomorphology, Sedimentology, Chronology, and Geochemistry)

Latitude: 29° 10' 7.20" N

Longitude: 76° 04' 7.20" E

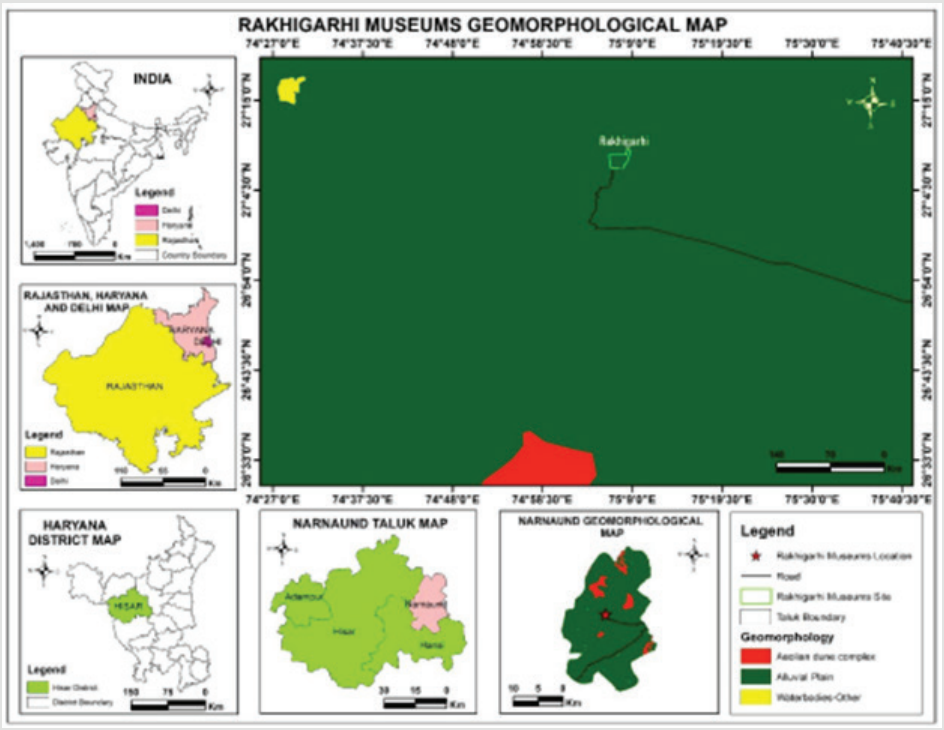


Figure 3:- Geomorphological Map of Rakhigarhi.



Figure 4:- Excavated mud-brick architectural remains exposed within one of the principal settlement mounds at Rakhigarhi



Figure 5:- Close-up view of the excavated mud-brick architectural remains preserved within the Rakhigarhi archaeological mound.

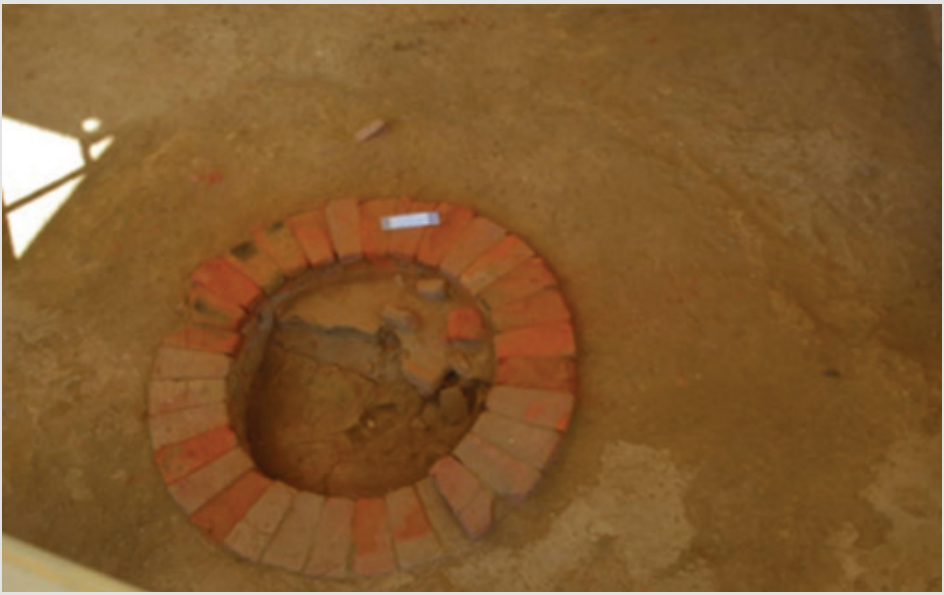


Figure 6:- Circular brick-lined well excavated at the Rakhigarhi archaeological site.



Figure 7:- Exposed archaeological section at Rakhigarhi showing layered cultural deposits containing brick fragments within the settlement mound.



Figure 8:- Parrot Wall at Rakhigarhi.

Rakhigarhi is situated in the Hisar district of Haryana within the Ghaggar–Chautang alluvial plain of northwestern India. The site occupies a relatively elevated interfluve setting developed on Quaternary alluvial deposits and consists of a cluster of archaeological mounds distributed across an extensive landscape. The present-day geomorphology is characterized by a flat to gently undulating alluvial plain with no visible active river channel adjacent to the archaeological site.

Regional geoarchaeological studies suggest that Rakhigarhi was established in proximity to buried paleochannel systems associated with the Ghaggar–Chautang drainage network. Geoelectrical resistivity surveys conducted in a wider region have identified subsurface sandy channel bodies interpreted as former river courses and potential groundwater reservoirs (Sinha et al., 2013). Although these paleochannels are not exposed within the archaeological excavations, they likely influenced settlement locations by providing access to groundwater, fertile floodplain soils, and seasonally available surface water.

The sedimentary succession in the region consists predominantly of unconsolidated Quaternary sands, silts, and clays deposited by fluvial and floodplain processes. These deposits record repeated episodes of channel migration, overbank flooding, and landscape reorganization during the Late Quaternary and the Holocene. Buried channel sands are particularly significant because they function as aquifers capable of storing and transmitting groundwater across semi-arid landscapes.

Chronologically, Rakhigarhi preserves one of the longest occupational sequences in the Indus Civilisation, spanning the Early Harappan, Mature Harappan, and Late Harappan phases (ca. 5000–1300 BCE). Recent chronostratigraphic and geomorphological studies indicate that major Himalayan-fed river systems, including the former Sutlej and Yamuna courses, had already shifted away from this region prior to the Mature Harappan period. Consequently, the settlement likely depended on monsoon-fed streams, groundwater stored within paleochannel sands, and locally managed water-storage systems rather than a perennial, glacier-fed river.

Geochemically, the alluvial sediments of the Ghaggar–Chautang basin show a mixed provenance derived from the Siwalik foothills and surrounding alluvial plains. Provenance studies suggest that by the Mature Harappan period, sediments deposited in the region no longer carried a dominant Higher Himalayan signature, supporting the interpretation that local monsoon-fed drainage systems had become the principal sources of water and sediment. This geoenvironmental setting provided a stable foundation for long-term human occupation and agricultural development in Haryana's semi-arid plains.

Geoheritage, Archaeological Heritage, and Cultural Significance of Rakhigarhi

Rakhigarhi represents one of the most significant geoarchaeological landscapes on the Indian subcontinent. The site preserves evidence of long-term interactions between human settlements, alluvial geomorphology, groundwater resources, and Holocene climatic variability within the Ghaggar–Chautang plains. Its Geoheritage value lies in demonstrating how ancient communities adapted to a semi-arid fluvial environment through water management, agricultural innovation, and strategic settlement planning.

Archaeologically, Rakhigarhi is one of the largest known urban centers of the Indus Civilization and has yielded evidence of Early, Mature, and Late Harappan occupations. Excavations have revealed habitation structures, drainage systems, craft production areas, ceramics, burial grounds, and water management features that collectively document more than three millennia of cultural development. The site has become increasingly important for understanding the origin, growth, and transformation of Harappan urbanism in Northwestern India. Field observations include a preserved brick-lined well, illustrating the importance of groundwater access and local water management infrastructure within the Harappan settlement. The excavated section exposed layered archaeological deposits composed predominantly of silty sediments, containing abundant brick fragments and anthropogenic material. Although these exposures represent the cultural stratigraphy of the settlement rather than the natural Quaternary succession, they illustrate the progressive accumulation of habitation deposits that produced the present-day archaeological mounds observed during the field excursion.

The 2019 ancient DNA study (Shinde et al., 2019) from the Rakhigarhi cemetery (RGR-3/4) provided the first genome-scale data from an Indus Civilization individual, demonstrating a genetic profile consistent with a mixture of ancient Iranian-related and Southeast Asian hunter-gatherer ancestries with no detectable Steppe pastoralist ancestry. This finding directly challenges the hypothesis that Steppe migrations were responsible for the spread of Harappan culture and provides independent genetic evidence for the autochthonous development of Harappan urbanism, as documented in archaeological stratigraphy.

Although Rakhigarhi is not currently inscribed on the UNESCO World Heritage List, it is widely regarded as one of the strongest Indian candidates for future nomination because of its exceptional archaeological significance, integrity, and contribution to understanding one of the world's earliest urban civilizations.

The broader heritage landscape of the region includes numerous Harappan and protohistoric sites distributed across Haryana and the Ghaggar–Hakra Plains. These associated sites provide important evidence of settlement networks, trade connections, agricultural systems, and environmental adaptation across the Indus Civilization.

The cultural significance of Rakhigarhi extends beyond archaeological significance. The surrounding villages preserve agricultural traditions, craft practices, and rural lifeways that continue to be closely linked to the alluvial landscape of the river. The traditional dependence on groundwater, seasonal rainfall, and fertile agricultural soils reflects a long history of human adaptation to the environmental conditions that originally supported settlements in this region. Rakhigarhi represents not only an archaeological site but also a living cultural landscape where geological processes, environmental resources, and human history remain closely interconnected.

Regional Geology of Kalibangan (Stratigraphy, Structure, Paleontology and Quaternary Geology)

Kalibangan is located in the Hanumangarh District of northern Rajasthan along the Ghaggar–Hakra paleodrainage system at the northeastern margin of the Thar Desert. Geologically, the region forms part of the northwestern Indo-Gangetic foreland basin, a vast sedimentary plain developed from Himalayan-derived sediments that were deposited during the Quaternary. The landscape surrounding Kalibangan is characterized by a low-relief alluvial plain with scattered archaeological mounds, agricultural fields, and sandy surfaces influenced by fluvial and aeolian processes.

The regional stratigraphy is dominated by unconsolidated Quaternary sediments, comprising channel sands, floodplain silts, clays, aeolian sands, and locally developed calcrete horizons. Subsurface investigations, including borehole records, sediment cores, geophysical surveys, and sediment provenance studies, have revealed thick successions of fluvial sands overlying finer grained floodplain deposits. These sediments record repeated episodes of river migration, floodplain aggradation, channel abandonment, and desert-margin sedimentation during the Late Pleistocene and the Holocene.

Structurally, the region lies within the Himalayan foreland basin and reflects long-term tectonic adjustments associated with the Himalayan uplift. Although no major active structures are exposed at the archaeological site, regional drainage evolution has been influenced by tectonically driven river reorganization within the Sutlej–Yamuna Interfluve. These large-scale geomorphic changes contributed to the development and eventual abandonment of major paleochannel systems in northwestern India.

The Quaternary geological significance of Kalibangan arises from its association with the Ghaggar–Hakra palaeovalley. Chronological, provenance, and geophysical studies indicate that a major fluvial system occupied this corridor during the Late Pleistocene and the Early Holocene. However, evidence suggests that large Himalayan-fed discharge had shifted away from the region before the Mature Harappan occupation. During the Harappan period, the landscape was likely sustained by monsoon-fed rivers, local runoff, groundwater recharge, and episodic flooding from the Siwalik foothill catchments.

Paleontological evidence from this region is limited because of the dominance of unconsolidated alluvial and aeolian deposits. Nevertheless, paleoenvironmental information is preserved in paleosols, carbonate nodules, phytoliths, pollen assemblages, and archaeobotanical remains recovered from archaeological contexts such as these. These records indicate fluctuations between relatively wet Holocene monsoon phases and progressively drier conditions during the Late Holocene.

During the field visit, the principal observable features included the archaeological mounds of Kalibangan, the surrounding alluvial plain, and the modern Ghaggar River corridor crossed en route to the site. The buried paleochannel architecture, fluvial stratigraphy, and sediment provenance relationships discussed in the literature are not directly visible at the surface and are primarily known from subsurface investigations and laboratory analyses. Consequently,

Kalibangan represents an important example of a geoarchaeological landscape in which much of the geological evidence for past river dynamics is preserved beneath the present-day land surface.

Flora, Fauna, Climate and Weather Conditions During Field Excursion

Kalibangan is situated in the semi-arid to arid transition zone of northwestern Rajasthan, near the northeastern margin of the Thar Desert. The region experiences a continental climate, characterized by extremely hot summers, cool winters, low annual rainfall, and high evapotranspiration. The average annual precipitation ranges from approximately 320–350 mm, with nearly 80% of the rainfall occurring during the southwest monsoon season between July and September. The area falls within the BSh–BWh transition of the Köppen climatic classification, representing a semi-arid steppe environment that locally grades into hot desert conditions.

Natural vegetation is dominated by drought-resistant xerophytic species adapted to low rainfall and high temperatures. Common plant communities include grasses and shrubs, such as Cenchrus spp., Calotropis procera, Capparis decidua (ker), Prosopis cineraria (khejri), and scattered Acacia species. Agricultural fields surrounding the archaeological site support the seasonal cultivation of wheat, mustard, cotton, bajra, and other crops where irrigation is available.

The fauna of the region is typical of semi-arid plains and desert-margin environments of Rajasthan. Commonly observed animals include nilgai (Boselaphus tragocamelus), blackbuck (Antilope cervicapra) in protected areas, desert fox, Indian hare, reptiles, and numerous bird species adapted to open grassland and agricultural habitats. Seasonal migratory birds may also occur in nearby wetlands and water bodies during winter.

During the field excursion, Kalibangan was observed as a broad, low-relief alluvial plain with sparse vegetation and extensive agricultural land. Archaeological mounds appeared as subtle topographic highs. Dry, clear weather, high solar radiation, low humidity, and good visibility enhanced the observation of the geomorphic setting, while sparse vegetation and exposed sediments provided favorable conditions for field investigation.

The climatic setting of Kalibangan is particularly significant from a geoarchaeological perspective because it illustrates the environmental challenges faced by Harappan populations that occupied the desert margin. Variations in monsoon intensity, groundwater availability, and seasonal flooding directly influence agriculture, settlement sustainability, and long-term human occupation within the Ghaggar–Hakra basin.

Literature Review

Kalibangan is one of the most extensively studied settlements of the Indus Civilization and occupies a central position in debates concerning Harappan urbanism, river dynamics, paleoclimate, and human adaptation in the semi-arid landscapes of northwestern India. Archaeological investigations conducted by the Archaeological Survey of India revealed a fortified settlement comprising both pre-Harappan and Mature Harappan occupational phases, well planned streets, drainage systems, fire altars, and the celebrated plowed agricultural field, which represents one of the earliest direct pieces of evidence for organized agriculture in South Asia.

Early research focused primarily on archaeology and settlement planning, whereas more recent studies have adopted geoarchaeological approaches. Remote sensing, sedimentological investigations, geophysical surveys, and chronometric dating have been used to reconstruct the evolution of the Ghaggar–Hakra paleodrainage system and its relationship with Harappan settlements. Geoelectrical resistivity surveys have identified buried paleochannel systems adjacent to several Harappan sites, including those within the broader Kalibangan region (Sinha et al., 2013). Subsequent geomorphological and chronological investigations have demonstrated that the Ghaggar–Hakra corridor preserves evidence of large paleofluvial systems that were active during the Late Pleistocene and Early Holocene.

A major advance came from sediment provenance and Optically Stimulated Luminescence (OSL) studies, which suggested that the large Himalayan-fed Sutlej River abandoned the Kalibangan paleovalley before the Mature Harappan period (Singh et al., 2017). Geochemical analyses of sediments and Harappan pottery further indicate that during urban occupation, the Ghaggar system was likely sustained by foothill-derived and monsoon-fed water sources rather than by a major glacier-fed river (Chatterjee and Ray, 2017). Additional studies have emphasized the role of buried channel sands, groundwater recharge, seasonal flooding, and monsoon variability in supporting the development of settlements within the Ghaggar–Hakra Basin.

Recent research has also linked Kalibangan to the broader Holocene climatic fluctuations. Multiple paleoclimate records from northwestern India suggest relatively humid conditions during the early to middle Holocene, followed by increasing aridity after approximately 4.2 ka BP. These environmental changes have been proposed as contributing factors in the transformation of Harappan settlement systems, although climate is increasingly viewed as one factor among several interacting social, economic, and environmental processes that shape human behavior.

Despite this significant progress, several important questions remain unresolved. The most debated issue concerns the hydrological conditions that prevailed during the Mature Harappan occupation of Kalibangan. While there is growing agreement that a major Himalayan-fed river was absent during this period, the magnitude, seasonality, and reliability of local water resources remain poorly understood. Similarly, the relative importance of groundwater, seasonal runoff, floodwater recharge, and local water management strategies have not yet been fully quantified. Another unresolved issue is the precise relationship between regional climatic deterioration and site specific patterns of

settlement continuity, adaptation, and abandonment.

Consequently, Kalibangan continues to serve as a key geoarchaeological locality for investigating the interactions among river dynamics, climate variability, groundwater resources, and urban development along the northwestern margin of the Indian subcontinent.

Location Description: Geomorphology, Sedimentology, Chronology and Geochemistry of Kalibangan

Latitude: 29° 28' 12.00" N | **Longitude:** 74° 07' 48.00" E

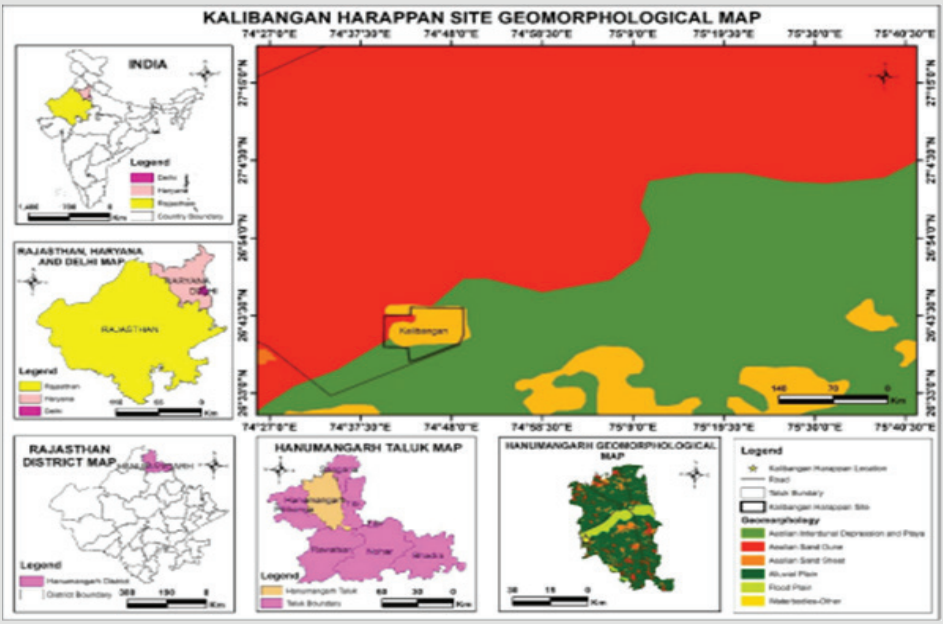


Figure 9:- Geomorphological Map of Kalibangan



Figure 10:- Museum reconstruction of a Harappan burial based on excavated funerary remains from Kalibangan, Rajasthan.



Figure 11:- Surface runoff has dissected the Kalibangan archaeological mound into an interconnected network of erosional gullies, exposing its internal sedimentary succession.

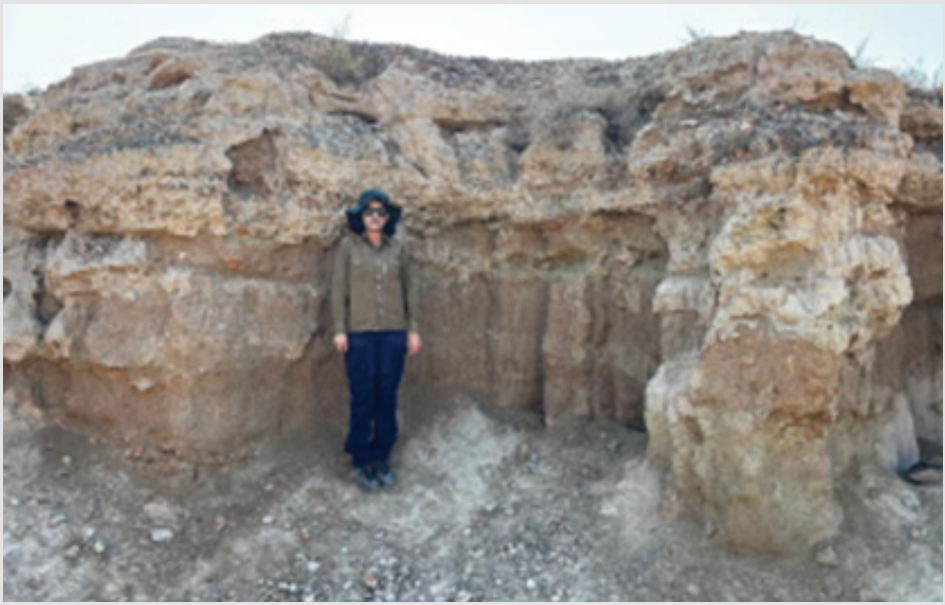


Figure 12:- Erosional exposure of the Kalibangan archaeological mound, showing the internal sedimentary and cultural deposits exposed by gully erosion.

Kalibangan is situated on the southern margin of the Ghaggar–Hakra paleovalley in the Hanumangarh District of northern Rajasthan. The site occupies a strategic position within the semi-arid alluvial plains at the northeastern edge of the Thar Desert. The archaeological complex comprises a series of settlement mounds developed on slightly elevated ground above the surrounding floodplain. The landscape is currently characterized by a low-relief alluvial plain, agricultural fields, sparse vegetation, and sandy surfaces influenced by both fluvial and aeolian processes.

Geomorphologically, Kalibangan lies within a broad paleodrainage corridor associated with the Ghaggar–Hakra river system. Although the paleochannel architecture is not directly visible at the archaeological site today, regional geomorphological studies indicate that the settlement was established along the margins of a major abandoned fluvial valley. This setting provides access to fertile alluvial soils, groundwater resources, and relatively stable terrain suitable for long-term occupation. During the field visit, the most prominent geomorphic features observable at the site were archaeological mounds and the extensive alluvial plain surrounding them.

The sedimentology of the region is dominated by unconsolidated Quaternary deposits, consisting of channel sands, floodplain silts, clays, and locally reworked aeolian sands. Borehole records, sediment cores, and geophysical investigations revealed thick subsurface accumulations of grey micaceous sands interpreted as former channel deposits, overlain by finer-grained floodplain sediments. These deposits record repeated phases of river migration, overbank flooding, channel abandonment, floodplain development, and desert-margin sedimentation during the Late Quaternary and Holocene.

Chronologically, Kalibangan preserves evidence of both Pre-Harappan and Mature Harappan occupations, spanning approximately the third millennium BCE. Geochronological investigations using Optically Stimulated Luminescence (OSL) dating and radiocarbon methods indicate that major Himalayan-fed fluvial activity in the Ghaggar–Hakra corridor predated the principal phase of Harappan urban occupation. Current evidence suggests that by the Mature Harappan period, the large Sutlej-fed river system had already shifted away from the region, leaving a landscape sustained primarily by monsoon-fed streams, groundwater recharge, and episodic flooding.

Geochemical and sediment provenance studies have provided important insights into the sources of sediments associated with the Ghaggar–Hakra system. Analyses of alluvial deposits and archaeological materials indicate a predominance of Siwalik foothill and local alluvial sediment sources during the Harappan occupation rather than continuous sediment input from the Higher Himalayan glacial catchments. These findings support the interpretation that Kalibangan developed within a monsoon-dominated fluvial environment rather than along an actively flowing, glacier-fed river.

During the field excursion, the modern Ghaggar River channel was observed as a low-gradient alluvial system characterized by fine-grained channel and floodplain sediments, providing the present-day geomorphic context for the broader Ghaggar Basin discussed in the literature.

Therefore, the geological setting of Kalibangan represents an important archive of Quaternary landscape evolution, river reorganization, climate variability, and human adaptation at the desert margin. The site remains one of the most significant geoarchaeological localities for understanding the interaction between changing fluvial systems and Harappan settlement development in Northwestern India.

Geoheritage, Archaeological Heritage, Nearby Heritage Sites, Customs and Culture

Kalibangan represents one of the most important geoarchaeological heritage landscapes in the Indian subcontinent. Its significance arises from the close relationship between human settlement, fluvial landscape evolution, and climatic variability along the Thar Desert margin. The site preserves evidence of how ancient populations adapted to changing water availability, alluvial environments, and semi-arid climatic conditions during the third millennium BCE. The surrounding Ghaggar–Hakra palaodrainage corridor constitutes an important component of the geoheritage of northwestern India because it records the interaction between Quaternary River dynamics, desert-margin geomorphology, and human occupation.

Archaeologically, Kalibangan is internationally recognized as one of the principal urban centers of the Indus Civilization. Excavations conducted by the Archaeological Survey of India have revealed both Pre-Harappan and Mature Harappan occupation levels, fortified settlements, planned streets, drainage systems, fire altars, burial grounds, and one of the earliest known archaeologically preserved plowed agricultural fields in the world. These discoveries have made Kalibangan a key reference site for understanding Harappan urbanism, agriculture, and environmental adaptations.

Field observations show that the archaeological mound is extensively dissected by erosional gullies, producing steep exposures that reveal accumulated anthropogenic deposits forming the present-day landform. This erosion provides a natural window into the internal structure of the mound while simultaneously contributing to its gradual degradation.

Although Kalibangan is not currently inscribed on the UNESCO World Heritage List, it forms part of the broader cultural landscape of the Indus Civilization, several components of which have been recognized internationally for their outstanding archaeological significance. The site possesses considerable potential for future geoheritage and archaeological heritage recognition because of its exceptional preservation and scientific importance.

Several important archaeological and historical sites are located within the broader regions of northern Rajasthan and Haryana. These include Harappan settlements distributed along the Ghaggar–Hakra corridor, including Rakhigarhi, Bhirrana, Kunal, Banawali, and numerous smaller, protohistoric sites. Together, these localities provide valuable evidence of settlement networks, trade, agricultural systems, and environmental adaptation across the northwestern Indian plains.

The cultural landscape surrounding Kalibangan continues to reflect the traditional rural life of northern Rajasthan. Agriculture remains the dominant occupation, with the cultivation of wheat, mustard, cotton, and millet supported by canal irrigation and groundwater resources. Traditional villages preserve local architectural styles, handicrafts, folk traditions, and agricultural practices that are closely linked to the semi-arid environment. Seasonal festivals, livestock rearing, and community-based farming continue to shape the region's social and economic life.

Kalibangan thus represents a unique combination of geological, archaeological, and living cultural heritage. The site demonstrates how environmental resources, climatic conditions, and human ingenuity combined to sustain settlements at the desert margin for thousands of years.

Location Description: Geomorphology, Stratigraphy, Structure, and Quaternary Geology of Sambhar Lake

Latitude: 26° 57' 59.99" N

Longitude: 75° 04' 60.00" E

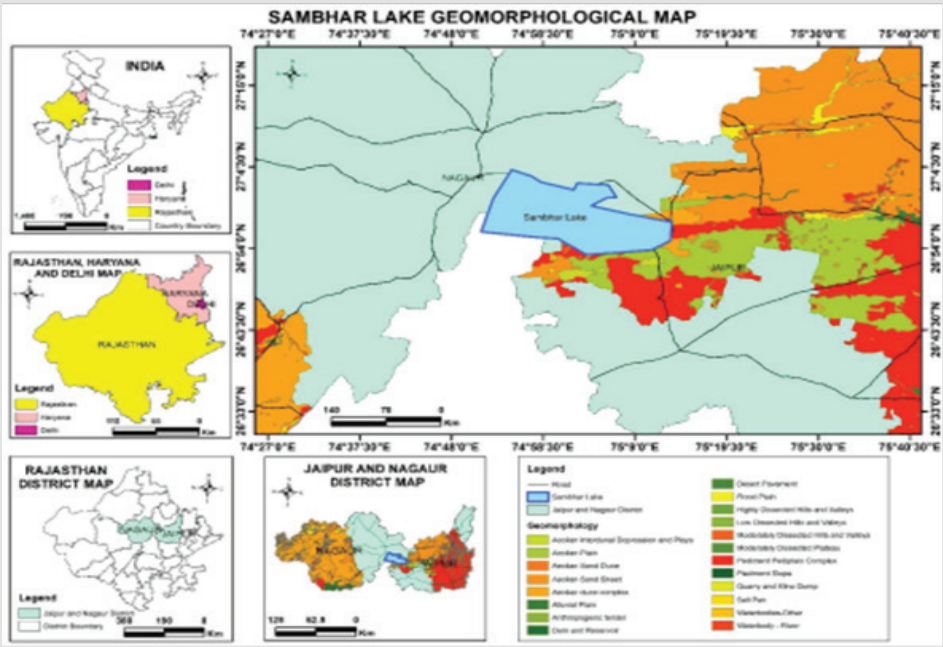


Figure 13:- Geomorphological Map of Sambhar Lake

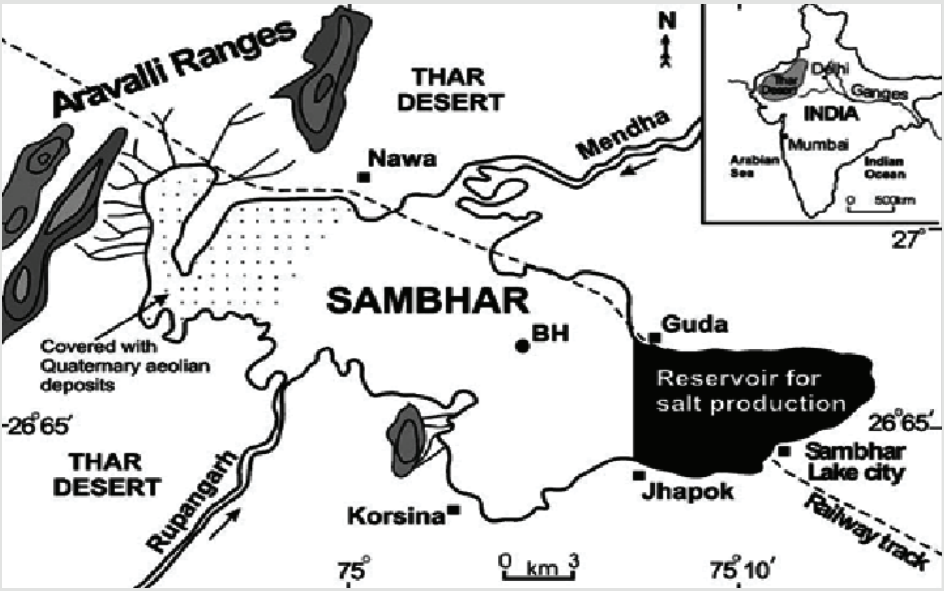


Figure 14:- Location map of Sambhar playa in the Thar Desert; the playa is fed by the river Mendha from the NE and the river Rupangarh from the SW (after Sinha and Raymahashay 2004). (Inset) Location of the Thar Desert in the Indian outline map. The easternmost part of the playa is used for salt production.



Figure 15:- Field view of Sambhar Lake playa showing the low-relief evaporitic basin floor, saline channel, and isolated basement knoll protruding above the Quaternary lake deposits. The protruding basement knoll (right background) represents an inlier of the Delhi Supergroup quartzite rising above the Quaternary playa floor, a geomorphological configuration that cannot be produced by aeolian or fluvial processes alone and requires structural control of the basin.



Figure 16:- Greater Flamingos (Phoenicopterus roseus) at Sambhar Lake. Flamingo populations are directly dependent on seasonal salinity and water level fluctuations driven by monsoon variability, linking avifaunal ecology directly to the Quaternary paleoclimate signal preserved in the lake's evaporite archive.



Figure 17:- Salt evaporation ponds at Sambhar Lake showing the engineered brine concentration system used for commercial salt production. Sequential evaporation in shallow ponds promotes halite precipitation under arid conditions.

Sambhar Lake is located approximately 80 km southwest of Jaipur in central Rajasthan and represents the largest inland saline lake in India. The lake occupies a broad, shallow depression surrounded by low hills of the Proterozoic Aravalli–Delhi Fold Belt. The basin forms an endorheic (internally drained) hydrological system in which inflowing water has no external outlet and is lost primarily by evaporation.

Regional Geology and Geomorphology

The modern landscape is dominated by an extensive playa environment characterized by saline mudflats, salt crusts, shallow brine pools, and seasonal waterbodies. The photographically documented field area shows a striking contrast between the nearly flat evaporitic lake floor and resistant rocky hills that rise above it.

The isolated bedrock hills within and around the basin represent erosional remnants of the Proterozoic basement, whereas the lake floor consists of younger unconsolidated sediments and evaporites. Seasonal flooding during the monsoon, followed by intense evaporation during the dry season, produces the characteristic salt-encrusted surfaces observed throughout the basin.

Quaternary Geology

The Quaternary history of Sambhar Lake has been reconstructed primarily using sediment cores and geomorphological investigations. Radiocarbon dating and sedimentological studies indicate that lacustrine deposits accumulated during wetter Holocene intervals and were subsequently modified by repeated evaporation and salt precipitation phases (Singh et al., 1972; Sinha et al., 2004).

A 23 m sediment core from the central playa records alternating clastic and evaporitic units that reflect fluctuations in lake level, salinity, and hydrological balance over the last ~ 25,000 years (Sinha et al., 2004). These sedimentary sequences preserve evidence of changing monsoon intensity and repeated transitions between wetter lacustrine and drier playa environments.

Geochemistry

Sambhar Lake is a hypersaline system dominated by sodium-chloride-rich brines. The lake contains economically important evaporite minerals, including halite and gypsum, together with carbonate and sulfate phases identified from sediment cores and surface deposits (Sinha et al., 2004). Variations in evaporite mineralogy and geochemical proxies have been interpreted as reflecting changes in the evaporation-to-inflow ratio over time, providing an important archive of paleoclimatic change in northwestern India.

Modern salt crusts, brine channels, and evaporative surfaces observed during the field excursion represent the latest stage in the long history of climatic and hydrological evolution preserved within the Sambhar Basin.

Flora, Fauna, Climate and Weather Conditions During Field Excursion

Sambhar Lake is situated in central Rajasthan at the eastern margin of the Thar Desert and experiences a hot semi-arid climate (Köppen BSh). The climate is characterized by high summer temperatures, low and highly seasonal rainfall, strong evaporation, and large annual temperature variation. The average annual rainfall ranges between approximately 500 and 600 mm, with most precipitation occurring during the Southwest Monsoon between July and September. For much of the year, evaporation exceeds precipitation, resulting in the progressive concentration of dissolved salts and the formation of extensive evaporite deposits across the lake basin.

Extensive salt-encrusted playa surfaces, shallow brine channels, exposed mudflats, and sparsely vegetated rocky slopes were observed throughout the excursion area of the lake. These conditions represent the modern evaporative phase of the lake's annual hydrological cycle and provide an excellent opportunity to observe the active salt accumulation processes.

The vegetation around Sambhar Lake is adapted to saline and semi-arid conditions. The surrounding rocky hills support sparse thorn-scrub vegetation dominated by drought-resistant species such as Acacia, Prosopis, Capparis, and Ziziphus. Salt-tolerant halophytic vegetation and grasses occur along the margins of the lake in areas affected by saline groundwater and periodic flooding. The relatively limited vegetation cover reflects low rainfall and high soil salinity.

Sambhar Lake is internationally recognized as an important wetland habitat for migratory and resident bird populations. Seasonal fluctuations in water levels and salinity create diverse ecological niches that support rich avifauna. The lake is particularly famous for large congregations of greater flamingos (Phoenicopterus roseus) and lesser flamingos (Phoeniconaias minor), which use the saline waters as feeding grounds. Other commonly recorded species include pelicans, avocets, stilts, gulls, terns, plovers, sandpipers, and numerous migratory waterfowl associated with the Central Asian Flyway.

The ecological significance of Sambhar Lake is directly linked to its geological and hydrological settings. Seasonal lake expansion and contraction control habitat availability, and variations in salinity influence biological productivity and species distribution. Consequently, Sambhar Lake represents an important example of the interaction between climate, hydrology, geomorphology,

evaporite formation, and biodiversity within an arid-zone saline lake ecosystem. Therefore, the lake serves not only as a significant geological and economic resource but also as one of India's most important inland wetland environments.

Literature Review

Sambhar Lake is India's largest inland saline playa and has long attracted attention because it preserves a valuable record of Quaternary environmental change, evaporite deposition, hydrological evolution, and possible neotectonics influences within the eastern margin of the Thar Desert. Research on the basin has focused primarily on its origin, sedimentary evolution, climatic history, and, more recently, its potential as a terrestrial analog for Martian evaporitic lake systems.

One of the most influential studies was that of Sinha and Raymahashay (2004), who analyzed a 23 m sediment core from the central basin and reconstructed the late Quaternary evolution of the lake. Their results documented alternating lacustrine and evaporitic phases, indicating repeated fluctuations between wet and dry climatic conditions. Based on sedimentological evidence, evaporite mineral assemblages, basin morphology, and regional geomorphic relationships, the authors proposed that the Sambhar depression originated through tectonic movements and was subsequently modified by aeolian deflation and climatic processes, respectively. They concluded that tectonic activity created the accommodation space necessary for lake development, whereas later climatic oscillations controlled sedimentation and salinity evolution.

The tectonic interpretation was further developed within the broader framework of neotectonic studies in Rajasthan. Sinha-Roy (2001) argued that several geomorphic features of the region, including enclosed depressions, drainage anomalies, river profile irregularities, and differential landscape uplift, reflect the continued tectonic influence along reactivated structures associated with the Aravalli–Delhi Mobile Belt. In this model, Sambhar Lake occupies a structurally influenced basin, whose morphology cannot be explained solely by climatic or deflationary processes. Importantly, these interpretations are based largely on regional geomorphology and drainage analysis rather than direct observations of exposed fault scarps within the modern playa.

Subsequent studies have shifted attention toward paleoclimate reconstruction. Sedimentological, mineralogical, and geochemical investigations have demonstrated that lake levels, salinity, and evaporite precipitation closely track changes in the Indian Summer Monsoon intensity during the late Quaternary. Variations in gypsum, halite, carbonates, and associated geochemical proxies

provide evidence of repeated transitions between relatively humid lacustrine phases and highly evaporative playa conditions. These records make Sambhar Lake one of the most important continental archives for understanding monsoon variability in northwestern India.

Recent studies have expanded the significance of Sambhar beyond regional geology. Singh et al. (2024) proposed the Sambhar Lake as a terrestrial analog for Martian evaporitic paleolakes. Their study highlighted the similarities in basin evolution, evaporite accumulation, hypersaline conditions, and wet-to-dry hydrological transitions. The authors argued that Sambhar Lake provides an accessible natural laboratory for investigating sedimentary processes, evaporite mineral formation, and potential biosignature preservation relevant to planetary exploration.

Despite substantial progress, several important questions remain. The relative contributions of tectonic subsidence, climatic forcing, and aeolian deflation to basin formation remain a topic of debate. Direct evidence linking specific faults to basin development is limited, and the timing and magnitude of Quaternary tectonic activity require further investigation using high-resolution geophysical surveys and chronological studies. Similarly, although Sambhar Lake has been

proposed as a Mars analog, detailed studies of microbial communities, biosignature preservation, and rover-scale detection techniques remain comparatively scarce. Future research integrating sedimentology, structural geology, geophysics, geochemistry, and astrobiology will therefore be essential for refining both the geological evolution of Sambhar Lake and its value as a planetary analog site.

Outstanding Research Issues

1. What was the relative role of tectonic subsidence versus climatic processes in the initial formation of the Sambhar Basin?
2. Can geophysical investigations identify the subsurface structures responsible for basin development?
3. How did Quaternary monsoon fluctuations influence lake-level variations and evaporite accumulation rates
4. What biosignatures can be preserved within Sambhar evaporites, and how relevant are they to Mars exploration?
5. Which Martian evaporitic basins provide the closest process-based analog to Sambhar Lake?

Location Description (Geomorphology, Sedimentology, Chronology, Geochemistry, and Planetary Significance) – Sambhar Lake

Sambhar Lake is located approximately 80 km southwest of Jaipur, Rajasthan, on the eastern margin of the Thar Desert. It is India's largest inland saline lake and occupies a closed (endorheic) basin surrounded by low hills composed predominantly of Proterozoic rocks from the Delhi Supergroup. The lake receives water from several ephemeral streams, including the Mendha, Rupangarh, Kharian, Khandel, and Samaod rivers, but has no external outlets. Consequently, dissolved salts accumulate within the basin through intense evaporation.

Geomorphologically, Sambhar represents a classic playa-lake system developed in an arid to semi arid environment. The lake floor consists of extensive mudflats, salt crusts, shallow brine pools, and active saltpan. Seasonal fluctuations in water levels produce alternating phases of flooding, evaporation, salt precipitation, and desiccation. Wind action also contributes to the redistribution of fine sediments around the basin margins, creating a landscape shaped by the interaction of fluvial, lacustrine, evaporitic, and aeolian processes.

Sedimentological investigations indicate that the basin contains alternating lacustrine and evaporitic deposits. Clay, silt, carbonate-rich sediments, gypsum horizons, and halite-bearing

layers record repeated transitions between wetter lake conditions and drier playa phases in the basin. These deposits preserve an important archive of environmental change in northwestern India and provide evidence of long-term variations in monsoon intensity and hydrological balance.

Chronological studies suggest that lacustrine sedimentation began during the early Holocene and developed over older sandy substrate (Singh et al., 1972). A 23 m sediment core recovered from the central basin records approximately 25,000 years of environmental history and documents repeated alternations between clastic sedimentation and evaporite formation (Sinha et al., 2004). Geochemical proxies, including Na/Al ratios, carbonate δ18O values, dolomite abundance, and evaporite mineral assemblages, indicate repeated fluctuations in lake salinity, evaporation rates, and water availability over time.

The geochemistry of Sambhar Lake is dominated by hypersaline Na–Cl brines produced by intense evaporative concentration. Halite is the principal economic mineral, although gypsum, calcite,

thenardite, polyhalite, and other evaporite minerals are also present. These minerals provide valuable evidence of paleohydrological changes and the evolution of saline lake systems under fluctuating climatic conditions.

An important field locality within the excursion is the Shakambhari Devi hill, situated along the lake margin. This rocky knoll provides one of the few direct exposures of the geological basement under the lake basin. Field observations indicate that the outcrop is composed mainly of quartzite, likely belonging to the Delhi Supergroup, with prominent milky quartz veins cutting through the host rock. Bedding or structural surfaces display moderate to steep dips (approximately 30°–60°), reflecting the prolonged tectonic and metamorphic history of the Aravalli–Delhi Fold Belt. From this elevated viewpoint, participants can observe the contrast between the ancient Proterozoic basement rocks and the much younger Quaternary playa sediments and evaporite deposits that occupy the basin floor. Although the tectonic origin of the basin has been proposed by several authors (Sinha-Roy, 2001; Sinha et al., 2004), the direct tectonic structures responsible for basin formation are not readily observable at this locality, emphasizing the distinction between field observations and regional geological interpretations.

Beyond its regional geological significance, Sambhar Lake has been proposed as a terrestrial analog for evaporitic paleolake environments on Mars (Singh et al., 2024). The combination of hypersaline brines, evaporite mineral precipitation, playa-lake evolution, and repeated wet–dry climatic cycles make the lake an excellent natural laboratory for studying processes comparable to those inferred for ancient Martian Lake basins. Consequently, Sambhar serves not only as an important Quaternary archive of environmental change in India but also as a valuable site for planetary geology and astrobiological studies.

Flora, Fauna and Climate, Weather Conditions During Field Excursion – Sambhar Lake

The region experiences a hot semi-arid climate (Köppen BSh), characterized by low annual rainfall, high evaporation rates, and significant seasonal temperature variations. The average annual rainfall ranges between 500 and 600 mm, with nearly 80% of the precipitation received during the southwest monsoon season (July–September). Summer temperatures frequently exceed 40°C, whereas winter temperatures may fall below 10°C during the night.

The field excursion is scheduled during the winter season (January–February), when the weather conditions are most favorable for geological observations. Daytime temperatures generally range between 20–25°C, with clear skies, low humidity, and good visibility across the lake basin. Winter rainfall is minimal and is usually associated with occasional disturbances in the west.

The vegetation around the lake is sparse and adapted to saline and semi-arid conditions. Common plant communities include halophytic (salt-tolerant) species such as Suaeda, Salicornia, and Aeluropus, and other salt-marsh vegetation occurring along the lake margins and seasonally inundated areas. The surrounding uplands support scattered thorn-scrub vegetation characteristic of the Rajasthan semi-arid zone, including Acacia, Prosopis, Capparis, and Ziziphus species.

Sambhar Lake is internationally important as a wetland ecosystem and seasonal habitat for migratory birds. The lake supports large populations of waterfowl, waders, and shorebirds in winter. The most iconic species is the Greater Flamingo (Phoenicopterus roseus), which uses saline waters and mudflats as feeding grounds. Lesser Flamingos (Phoeniconaias minor) are also recorded periodically. Other commonly observed species include avocets, stilts, sandpipers, gulls, terns, pelicans, ducks, and various migratory waterbirds that arrive via the Central Asian Flyway.

The ecological significance of Sambhar Lake is closely linked to its geological and hydrological settings. Seasonal fluctuations in lake water levels control salinity, brine chemistry, microbial productivity, and food availability for migratory birds. Consequently, Sambhar Lake represents an important example of the interaction between climate, geology, hydrology, and ecology within an arid-zone saline lake system.

Geoheritage, Cultural Heritage, Archaeological Sites in the Vicinity, Cuisine and Culture – Sambhar Lake

Sambhar Lake is one of the most significant geoheritage landscapes in northwestern India. As the country's largest inland saline lake, it preserves a unique combination of geological, geomorphological, hydrological, ecological and cultural features within a single landscape. The lake provides an exceptional opportunity to observe active evaporite formation, saline playa processes, Quaternary environmental changes, and interactions between geology and human resource utilization. Recent studies have also highlighted its importance as a terrestrial analog for evaporitic paleolake environments on Mars, further enhancing its scientific value (Singh et al., 2024).

Sambhar also has considerable industrial heritage. Salt has been extracted from the lake for centuries and continues to be one of the most important economic activities in the basin today. Traditional and modern salt-production methods can be observed during field excursions, including brine concentration ponds, crystallization pans, pumping systems, and salt-harvesting operations. The historic Sambhar Salt Railway and associated colonial infrastructure provide additional evidence of the lake's role in the economic development of Rajasthan in the nineteenth

The surrounding region reflects the cultural traditions of rural Rajasthan, India. Local communities maintain livelihoods linked to salt production, agriculture, animal husbandry, and tourism in the region. Owing to its unique geological history, active evaporitic processes, cultural significance, ecological diversity, and growing relevance to planetary geology research, Sambhar Lake has strong potential for future recognition as a nationally important geoheritage site and geotourism destination.

Field Budget

Component	Basis of Calculation	Cost per Participant (INR)
Ground Transportation		
Delhi -Rakhigarhi	160 km × ₹15/km ÷ 5 participants	₹480
Rakhigarhi - Hanumangarh	310 km × ₹15/km ÷ 5 participants	₹930
Hanumangarh - Kalibangan (Return)	90 km × ₹15/km ÷ 5 participants	₹270
Hanumangarh-Sambhar Lake	460 km × ₹15/km ÷ 5 participants	₹1,380
Sambhar Lake-Delhi	355 km × ₹15/km ÷ 5 participants	₹1,065
Transportation Subtotal		**₹4,125**

Lucknow to Delhi Flight	(economy) | IndiGo/Air India one-way	**₹4,000**
Accommodation		
Rajvi Palace Hotel (or equivalent), Hanumangarh	₹3,000/night × 2 nights (Twin Sharing)	₹6,000
Hotel Anand Bagh (or equivalent), Sambhar	₹2,500/night × 2 nights (Twin Sharing)	₹5,000
Accommodation Subtotal		**₹11,000**
Meals	Breakfast & Dinner (₹600/day × 5 days) (Lunch excluded)	₹3,000
Sambhar Salt Toy Train	Per participant	₹1,000
Kalibangan Museum Entry	ASI Entry Ticket	₹20
Field Guide & Consumables	Printed guidebook, maps, stationery, field materials	₹5,00
Subtotal (Before Contingency)		**₹19,645**
Contingency (10%)	Unforeseen field expenses	₹1,965
Grand Total per Participant		**₹25,610**

Conclusion

This field excursion demonstrates how Quaternary landscape evolution, climatic variability, hydrological change, and human occupation are closely interconnected in northwestern India. The three field localities—Rakhigarhi, Kalibangan, and Sambhar Lake—provide complementary records of environmental change preserved within the alluvial plains, paleochannel systems, archaeological landscapes, and saline playa deposits.

At Rakhigarhi and Kalibangan, participants examine the geoarchaeological relationship between Harappan settlements and the Quaternary evolution of the Ghaggar-Hakra Alluvial Plains. Although the buried paleochannel systems discussed in the literature are not directly exposed at the surface, archaeological excavations, modern geomorphology, and regional geological studies illustrate how groundwater availability, monsoon-fed drainage, and floodplain evolution influenced settlement development and long-term human adaptation during the Holocene.

At Sambhar Lake, the excursion provides an opportunity to investigate the interactions between Proterozoic basement geology, Quaternary playa evolution, evaporite sedimentation, and

modern salt production. Field observations of quartzite basement exposure at Shakambhari Hill, together with the surrounding playa landscape and evaporite deposits, demonstrate the striking contrast between the ancient geological framework and the much younger sedimentary archive preserved within the basin. Published geomorphological and sedimentological studies further suggest that both tectonic processes and Quaternary climatic fluctuations have contributed to the evolution of the Sambhar Basin, although the structures responsible for basin development are not directly exposed at the field localities visited during this excursion.

Beyond their regional significance, these sites collectively illustrate how geological processes have influenced water availability, landscape evolution, ecosystem development, and the emergence of

complex human societies in semi-arid environments in the past. Sambhar Lake additionally provides an important terrestrial analogue for evaporitic paleolake systems on Mars, linking Quaternary geology with contemporary questions in planetary science and astrobiology. Despite decades of research, important questions remain concerning the chronology of paleochannel evolution, groundwater dynamics during the Harappan period, the relative influence of tectonics and climate on Sambhar Basin evolution, and the preservation of evaporitic biosignatures relevant to planetary exploration in this region. The field excursion therefore not only introduces participants to internationally significant geological and archaeological localities, but also highlights opportunities for future interdisciplinary research integrating Quaternary science, geoarchaeology, geomorphology, geophysics, geochemistry, and planetary geology.

Acknowledgements

The excursion leaders gratefully acknowledge the Archaeological Survey of India (ASI) for granting permission to visit the archaeological sites at Rakhigarhi and Kalibangan, India. We are especially grateful to Dr. Om Prakash Kumar Pandit (Archaeological Survey of India) for his assistance and guidance during our field visit to Rakhigarhi.

We sincerely thank the Saraswati River Rejuvenation Project, Government of Haryana, for their support in locating and interpreting the paleochannel landscape associated with the Saraswati–Ghaggar system during reconnaissance.

The authors acknowledge the support and encouragement of the INQUA Organising Committee in developing this proposed field excursion. We are particularly grateful to Dr. Anupam Sharma, Dr. Pradeep Srivastava, Dr. Binita Phartiyal, and Dr. Shailendra Agrawal for their valuable discussions, scientific guidance, and encouragement during the preparation of this field guide.

The authors also acknowledge the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, for the financial and logistical support that facilitated field reconnaissance and the preparation of this excursion guide.

Finally, we acknowledge the contributions of numerous researchers whose published work on the Quaternary geology, geoarchaeology, paleoclimate, geomorphology, and planetary significance of northwestern India has formed the scientific foundation of this guide. In particular, Rajiv Sinha, B. C. Raymahashay, S. Sinha-Roy, H. S. Saini, Yama Dixit, Cameron A. Petrie, Ajit Singh, and their collaborators have substantially advanced the understanding of the geological evolution of the Ghaggar–Hakra Basin and Sambhar Lake.

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Annexure

Field Excursion Guidelines: Do's and Don'ts

To ensure the safety of all participants and to promote responsible scientific field practices, all participants are requested to adhere to the following guidelines throughout the field excursions.

Keep a valid passport (for international participants) or a government-issued photo ID (for Indian participants) with you at all times during the field excursion.

Do's	Don'ts
1. Follow the instructions of the excursion leaders, coordinators, and local authorities at all times.	1. Do not collect rocks, fossils, archaeological artefacts, biological specimens, or any other materials without prior authorization.
2. Remain with the group and inform the excursion leader before leaving the designated route.	2. Do not damage, deface, or remove material from geological outcrops, caves, monuments, heritage structures, or other natural features.
3. Wear appropriate field attire, including sturdy closed-toe footwear, full-length trousers, a hat or cap, and weather-appropriate clothing.	3. Do not wander alone or separate from the excursion group without informing the field leaders.
4. Carry sufficient drinking water, personal medications, sunscreen, insect repellent, and other essential field supplies.	4. Do not climb unstable slopes, cliffs, rock formations, or enter hazardous areas unless specifically instructed or supervised.
5. Keep a valid photo identification and your excursion registration details with you during travel.	5. Do not swim or enter rivers, lakes, lagoons, or coastal waters unless expressly authorized by the excursion leaders.
6. Respect local customs, religious sites, cultural heritage, and private property.	6. Do not consume alcohol, recreational drugs, or engage in unsafe or irresponsible behaviour during the excursion.
7. Follow the Leave No Trace principles by carrying back all waste and helping to keep field sites clean.	7. Do not operate drones or other restricted equipment without obtaining the necessary permissions.
8. Use designated trails and approved observation areas to minimise environmental disturbance.	

9. Observe geological, ecological, archaeological, and cultural features carefully without causing any damage.

10. Record field observations systematically and collect samples only with prior permission from the excursion leaders and the relevant authorities.

11. Exercise caution near cliffs, riverbanks, caves, unstable slopes, road cuts, and other potentially hazardous terrain.

12. Respect wildlife by maintaining a safe distance from animals, birds, reptiles, insects, and their habitats.

13. Immediately report any illness, injury, emergency, or hazardous situation to the excursion organizers.

14. Be prepared for changing weather conditions and comply with all safety advisories issued by the excursion leaders.

8. Do not photograph restricted installations, sensitive locations, or local residents without prior permission.

9. Do not create excessive noise or disturb local communities, religious activities, wildlife, or natural habitats.

10. Do not leave valuables unattended or rely solely on mobile phone connectivity in remote areas.

11. Do not undertake any activity that may compromise your safety, the safety of fellow participants, or the conservation of the area's geological, ecological, archaeological, or cultural heritage.

Disclaimer

Participation in the field excursions is entirely at the participant's own risk. While the Organising Committee and excursion leaders will make every reasonable effort to ensure participant safety and provide appropriate guidance, they shall not be held responsible for any personal injury, illness, loss of personal belongings, property damage, delays, or unforeseen incidents arising during travel or field activities. Participants are expected to act responsibly, follow all instructions issued by the excursion leaders, and comply with applicable local laws and regulations throughout the excursion.













Scan for
Field Guide Book

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