

PALAEOSCIENCE TODAY

TRACING TIME, TELLING STORIES

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SPECIAL ISSUE

on

CLIMATE CHANGE



Birbal Sahni Institute of Palaeosciences

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The Director,

Birbal Sahni Institute of Palaeosciences (BSIP),
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Phone: +91-522-2740470 / 2740413 / 2740411

E-mail: director@bsip.res.in, palaeosciencetoday@bsip.res.in

Website: <http://www.bsip.res.in>

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From the Chief Editor's Desk

WHEN THE HIMALAYA SPEAKS THROUGH ICE AND ROCK: READING THE WARNING SIGNS OF A CHANGING MOUNTAIN SYSTEM

ON the morning of 26 August 2026, a catastrophe unfolded in the high Himalaya with extraordinary speed. A massive mass of glacier ice and bedrock detached from the mountain at an elevation of approximately 5,200 metres a.s.l. in the Langtang region of Nepal. The collapsing mass transformed into an enormous ice-rock avalanche, descended more than a kilometre towards the valley and generated a devastating cascade of debris and floodwater through the Lhende Khola and Bhote Koshi - Trishuli river system.



Within minutes, a remote high-altitude geological process had become a human catastrophe.

The event destroyed settlements, bridges, roads, hydropower infrastructure and vital trans-Himalayan connectivity. Its effects propagated far downstream, demonstrating once again that in the Himalaya, **what begins high in the mountains does not necessarily remain a mountain hazard.**

At first, the event was widely described as a cloudburst or flash flood. Subsequent scientific investigation has revealed a much more complex story – one involving the **cryosphere, geosphere and hydrosphere acting together in a rapidly evolving cascade.** For *Palaeoscience Today*, this distinction is particularly important.

Beyond the “Cloudburst”

A cloudburst is a meteorological phenomenon: exceptionally intense rainfall over a small area and

short duration. The Rasuwa disaster, however, increasingly appears to have originated from a **high-elevation failure of glacier ice and bedrock**, rather than from rainfall alone. Satellite imagery, video observations, seismic records and numerical analysis indicate that a large ice-rock mass collapsed and entered the Lhende Khola. As the avalanche descended, it fragmented, incorporated water and sediment and rapidly evolved into a powerful debris-rich flow. The distinction is not merely semantic. It changes the way we understand the hazard – and, more

importantly, how we should attempt to monitor it.

When a Mountain Becomes a Seismic Source

One of the most intriguing scientific findings from this event is the seismic signal generated by the collapse. The mass movement produced a signal equivalent to approximately **magnitude 5.2**, initially contributing to uncertainty about whether an earthquake had triggered the disaster. Subsequent analysis indicates that the seismic energy was generated by the enormous glacier – rock collapse itself.

This observation opens an important new field of investigation. Seismology is traditionally associated with earthquakes. But large landslides, rock avalanches and glacier collapses also release mechanical energy capable of generating detectable seismic waves. Could future seismic networks therefore help identify large cryospheric failures in near real time? This is a question that deserves serious research.

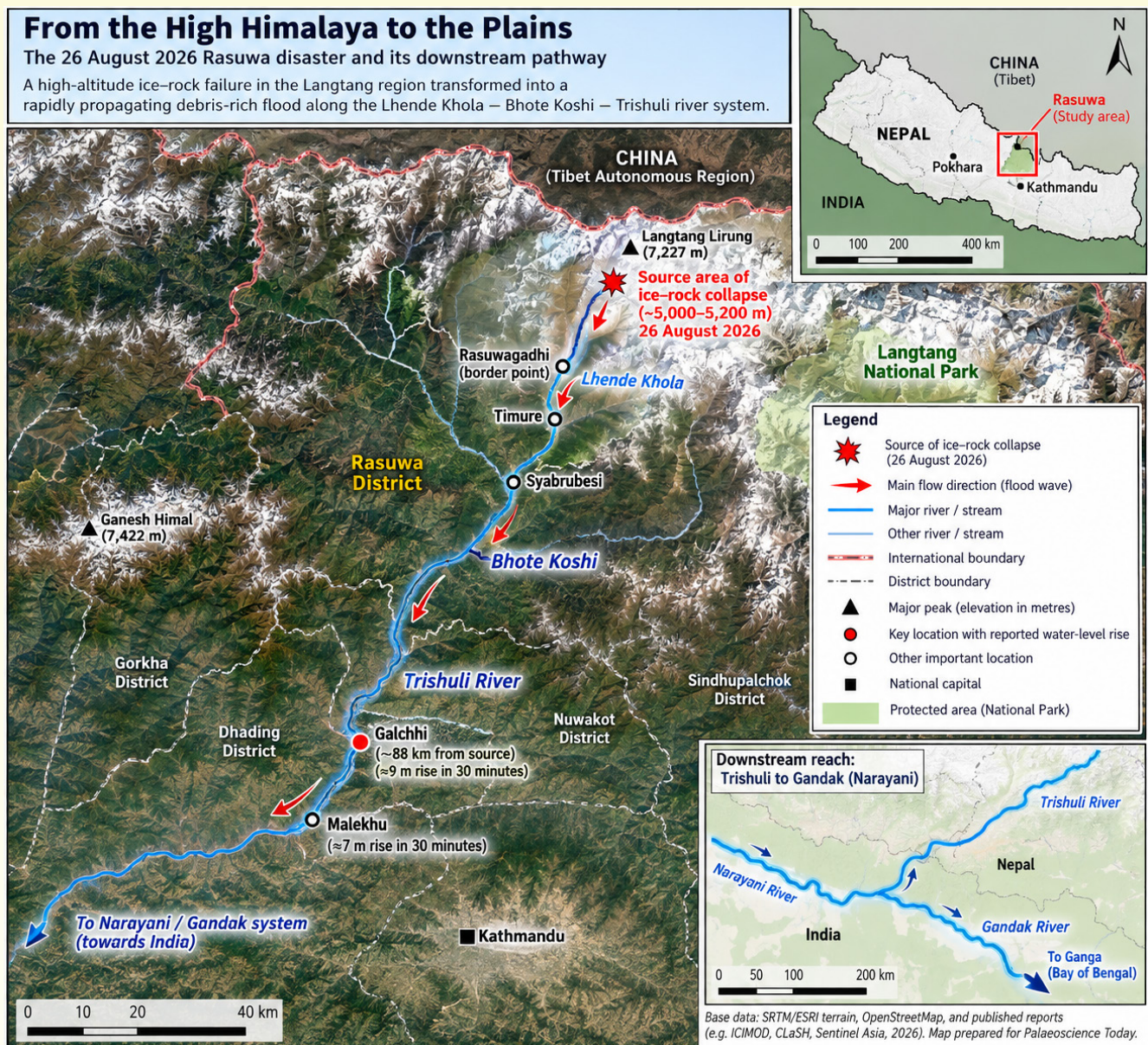


Figure 1. Location of the 26 August 2026 Rasuwa disaster and the downstream pathway from the high Himalayan source area through Lhende Khola, Bhote Koshi and Trishuli. The event illustrates how a high-altitude slope failure can propagate its effects far downstream.

A Cascade, not a Single Hazard

The Rasuwa event demonstrates the concept of **cascading hazards** with extraordinary clarity.

A simplified sequence is:

glacier–bedrock failure → ice–rock avalanche → rapid downslope flow → entrainment of water and sediment → debris-rich flood → river-chan-

nel transformation → downstream destruction.

Earlier interpretations focused strongly on the possibility that the avalanche temporarily blocked the river and subsequently produced a dam-break flood. More recent assessments suggest that the catastrophic flow may have remained largely continuous, with the avalanche itself displacing and entraining water as it moved rapidly downstream. The precise hydraulic

evolution continues to be investigated. This is scientifically important because it shows that a destructive Himalayan flood does not necessarily require a conventional glacial lake outburst flood. The **ice and rock themselves can become the initiating agent of the flood.**

The Extraordinary Speed of the Himalaya

Perhaps the most disturbing feature of the disaster is its speed. The initial collapse occurred at high altitude, but the resulting flow travelled rapidly through steep, confined Himalayan valleys. Once concentrated within the river corridor, water, ice, sediment and boulders could move enormous distances in a very short period. This explains the extraordinary rise in river levels reported downstream and the extensive destruction along the Bhote Koshi–Trishuli corridor. It also exposes a fundamental weakness in conventional flood-warning systems. River gauges can tell us that a flood is arriving. But they cannot necessarily tell us **why the flood has suddenly begun.** A rainfall-based warning system may be excellent at anticipating a monsoon flood and still fail to detect a sudden glacier–rock avalanche originating several kilometres above the river. This is the new challenge facing Himalayan disaster science.

The Cryosphere Is More Than Frozen Water

The term *cryosphere* is often used simply to describe glaciers, snow and ice. But in mountain systems, the cryosphere is deeply connected with the stability of the surrounding geosphere. When glaciers retreat and thin, the physical conditions of adjacent slopes change. Ice that once occupied valleys and buttressed mountain flanks disappears. Previously buried rock becomes exposed. Meltwater can penetrate fractures. Glacial and supraglacial lakes can expand. Ice-rich ground and permafrost can degrade. Large volumes of unstable sediment can accumulate. Thus, the loss of ice can also become a **change in mountain mechanics.** This is why the consequences of Himalayan warming cannot be measured only in square kilometres of glacier area lost. We must also ask: **What happens to the stability of the mountain after the ice has gone?**

Climate Change: Background Condition, Not a Convenient Explanation

The Rasuwa disaster also teaches us how carefully climate attribution must be handled. It would be sci-

entifically inappropriate to say that “climate change caused the flood.” The immediate cause appears to have been a sudden high-altitude ice–rock collapse, while the exact preconditioning mechanisms remain under investigation. ICIMOD has itself cautioned that the specific role of warming, permafrost degradation and other long-term changes in this particular collapse has not yet been established.

But this does not mean that climate change is irrelevant. Quite the opposite.

The Hindu Kush Himalaya is experiencing substantial cryospheric change. ICIMOD’s recent glacier assessment documents accelerating glacier mass loss since 2000 and emphasises that long-term observations show a predominantly negative mass balance across the region. Climate change therefore acts more appropriately as a **background risk modifier or amplifier.** It can alter the state of the system in which an avalanche, landslide or flood occurs. The distinction between **trigger** and **preconditioning** is fundamental: **The trigger may be sudden; the vulnerability may have been developing for decades.**

Two Disasters in Fourteen Months

The significance of Rasuwa becomes even greater when we look at the recent history of the same watershed. In July 2025, a different cryospheric event occurred in essentially the same Lhende Khola–Bhote Koshi corridor when a supraglacial lake associated with the Purepu Glacier drained rapidly. That event killed people and destroyed infrastructure, including the border bridge at Rasuwagadhi. Fourteen months later, the same corridor experienced a much larger disaster – but through a different mechanism.

This distinction is crucial. It tells us that the hazard is not simply “**glacial lake outburst floods.**” The broader hazard is **cryosphere instability.** Different parts of the cryosphere can fail in different ways:

glacial lake → GLOF

glacier + bedrock → ice–rock avalanche

unstable slope → landslide/debris flow

permafrost degradation → rockfall/slope collapse

extreme rainfall → landslide/flood

And these processes can interact.



Figure 2: Conceptual reconstruction of the cascading hazard sequence during the Rasuwa disaster: high-altitude ice–rock failure generated a rapidly moving mass that interacted with water and sediment, transforming a mountain-slope collapse into a destructive flood/debris-flow cascade.

The Himalaya as a Coupled Earth System

The traditional approach to natural hazards tends to divide the Earth into separate compartments:

- ❖ earthquakes belong to seismology;
- ❖ landslides belong to geomorphology;
- ❖ glaciers belong to glaciology;
- ❖ floods belong to hydrology;
- ❖ extreme rainfall belongs to meteorology.

The Rasuwa disaster demonstrates why these boundaries are increasingly inadequate.

The Himalaya is a **coupled Earth system**.

The atmosphere influences snow and ice.

The cryosphere influences slope stability.

Slope failure generates sediment.

Sediment changes river behaviour.

River behaviour determines downstream flood risk.

Human infrastructure determines the scale of the disaster.

The complete hazard therefore emerges from the **interaction of systems**, not from one system acting independently.

The Hidden Hazard Beneath the Ice

One of the most difficult scientific challenges is that the most dangerous instability may not always be visible. A glacial lake can be mapped from space. A retreating glacier can be measured. But a fracture

propagating through bedrock beneath or adjacent to a glacier may remain hidden until the moment of failure. ICIMOD specialists have emphasised precisely this limitation: sudden ice–rock avalanches can originate from unstable slopes or subsurface conditions that are difficult to detect using conventional monitoring. This means that future Himalayan monitoring must evolve from **surface observation to three-dimensional understanding of mountain stability**.

Satellite radar interferometry, high-resolution optical imagery, LiDAR, photogrammetry, seismic monitoring, ground-temperature measurements, geophysical imaging and AI-assisted change detection should be integrated wherever possible.

From Early Warning to Early Understanding

The conventional idea of early warning assumes that a measurable precursor exists.

But what if the event has almost no observable precursor?

Then the solution cannot simply be another alarm system.

We need **early understanding**.

That means identifying hazardous slopes before they fail, mapping potential avalanche pathways, modelling downstream flow propagation and identifying communities and infrastructure located within possible runout corridors. In other words: **The best early warning may begin years before the disaster – with hazard mapping, monitoring and risk-informed planning.** This is particularly important for Himalayan infrastructure. Roads, hydropower projects, bridges, tunnels, settlements and tourism facilities are expanding rapidly into mountain valleys. Infrastructure designed using today's environmental conditions may remain operational for several decades under a substantially different future climate and cryospheric regime. Environmental impact assessment at the time of construction is therefore not enough. We increasingly need **lifetime mountain-hazard assessment**.

A New Research Agenda for the Himalaya

The Rasuwa disaster should lead to a coordinated scientific programme built around several questions.

First, where are the unstable ice–rock systems?

High-resolution satellite and DEM-based mapping should identify potentially unstable glacier termini, hanging glaciers, steep fractured slopes and newly exposed bedrock.

Second, what is happening beneath the surface?

Permafrost temperature, fracture networks, ground-water movement and subsurface ice should be investigated using boreholes, electrical resistivity, seismic methods and other geophysical techniques.

Third, can mass movements be detected seismically?

The Rasuwa event provides an exceptional natural laboratory for distinguishing seismic signatures of tectonic earthquakes from those of large landslides and ice–rock avalanches.

Fourth, how far can a cascade travel?

Coupled numerical models should simulate the transition from avalanche to debris flow to river flood and determine downstream arrival times, inundation depths and sediment transport.

Fifth, how often has this happened before?

This is where palaeoscience becomes indispensable.

Reading the Geological Memory of the Himalaya

The Himalaya has experienced such processes long before satellites, hydrological gauges or modern climate observations existed. Its valleys preserve the evidence. Large boulders deposited far from their source, chaotic diamictos, debris-flow fans, lake sediments, buried soils, moraines, abandoned channels and disturbed sedimentary sequences can preserve the signatures of prehistoric extreme events. These deposits are the **memory of the mountains**.

If we systematically investigate them, we may discover that apparently unprecedented events have occurred repeatedly during the Late Pleistocene and Holocene – perhaps under climatic and geomorphic conditions very different from those of today. Palaeoscience can therefore answer a question that instrumental records cannot:

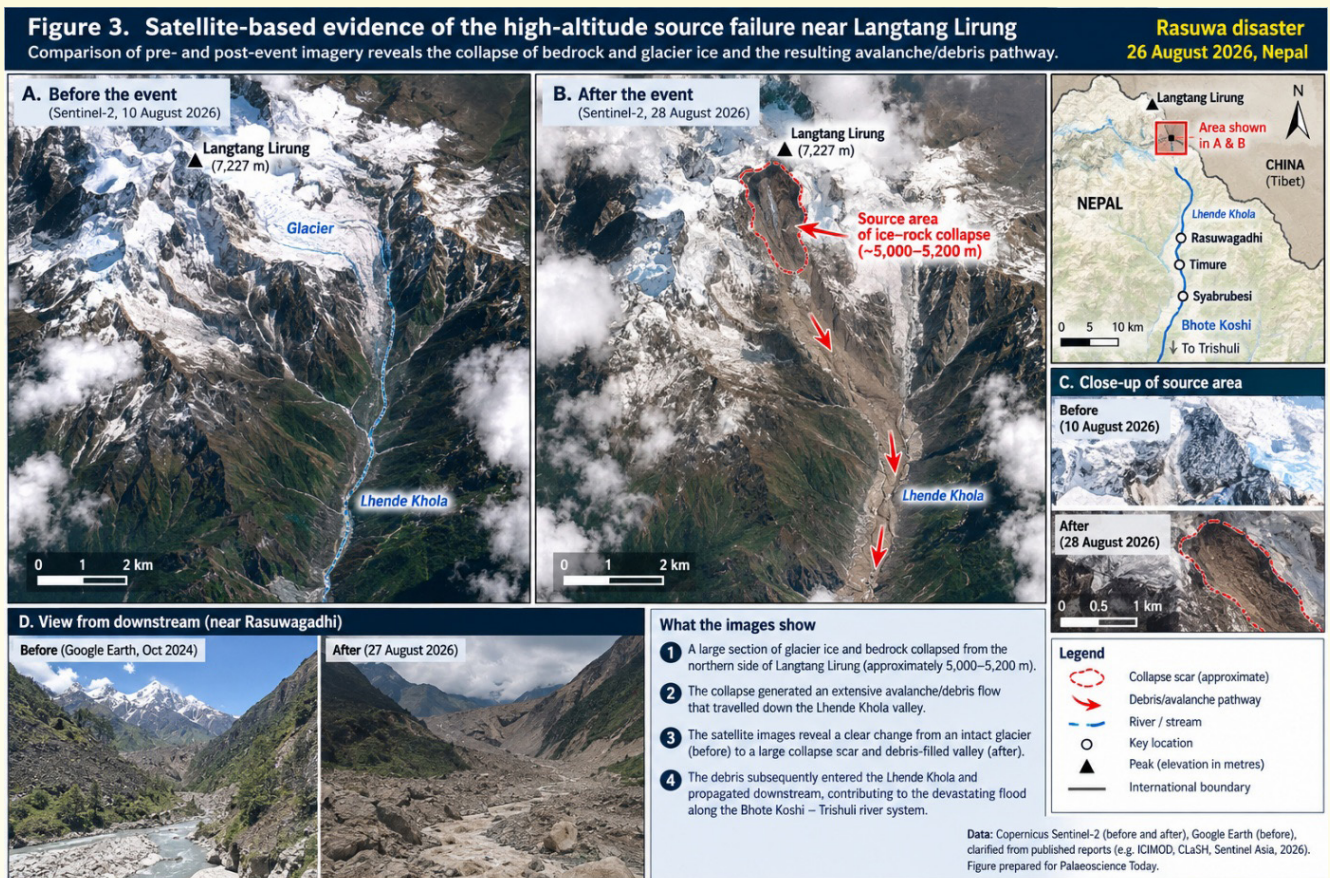


Figure 3: Satellite-based evidence of the high-altitude source failure near Langtang Lirung. Comparison of pre- and post-event imagery reveals the collapse of bedrock and glacier ice and the resulting avalanche/debris pathway.

What is the natural range of Himalayan extreme events over centuries to millennia? That knowledge is essential if we are to determine whether present-day events are truly exceptional or whether their frequency, magnitude or spatial distribution is changing.

Today's Disaster Is Tomorrow's Geological Archive

There is an almost poetic symmetry in this.

The Rasuwa disaster is currently a humanitarian tragedy.

But over decades and centuries, the flood deposits left along the river will become part of the geological record.

Today's boulders will become tomorrow's stratigraphic markers.

Today's debris fan may become tomorrow's palaeohydrological archive.

Today's glacier collapse may eventually be reconstructed from the sedimentary record by scientists who were not yet born when the disaster occurred.

This is one of the central lessons of palaeoscience:

The Earth remembers events long after human memory has forgotten them.

From Hazard Mapping to Hazard Forecasting

The next generation of Himalayan science must therefore move beyond isolated hazard inventories.

We need an integrated **Himalayan Cryosphere–Hazard Observatory** linking:

satellite remote sensing + glaciology + permafrost science + geomorphology + seismology + hydrology + meteorology + palaeoscience + artificial intelligence.

Such a system should continuously monitor the mountain-to-river continuum:

glacier → unstable slope → avalanche → lake or river blockage → debris flow → river → infrastructure → community.

And because Himalayan rivers cross national boundaries, the monitoring system must also cross political boundaries. The flood does not recognise a border. Our scientific cooperation should not either.

A New Way of Thinking About Himalayan Risk

The Rasuwa disaster should change one fundamental assumption.

We have traditionally asked:

“Will heavy rainfall produce a flood?”

We must now also ask:

“What is happening in the high mountains that could suddenly produce a flood?”

That is a profound shift.

It moves us from **rainfall-centric flood forecasting** towards **source-to-sink hazard assessment**.

The source may be a glacier.

The trigger may be a slope collapse.

The pathway may be a river.

The amplification may occur through sediment entrainment.

The final impact may occur hundreds of kilometres away.

Only by understanding the entire chain can we understand the disaster.

Listening to the Himalaya

The Rasuwa catastrophe is ultimately a story of connectivity.

Ice became unstable.

Rock became mobile.

The avalanche interacted with water.

Water acquired sediment and enormous momentum.

The river transmitted that energy downstream.

Human settlements and infrastructure stood in its path.

A geological process that began at 5,200 metres became a societal catastrophe far beyond the mountain itself.

The Himalaya is therefore telling us something important.

It is not simply **losing ice**.

It is **changing its behaviour as a mountain system**.

We cannot yet predict precisely when the next glacier–rock collapse will occur, nor can every sudden-onset hazard be forecast with useful lead time. But we can identify vulnerable slopes, map potential pathways, reconstruct prehistoric events, monitor changing cryospheric conditions and design infrastructure and communities with the possibility of cascading hazards in mind. And this is where palaeoscience has an important role to play.

The past provides the baseline.

The present provides the warning.

And the future demands that we connect the two.

The Himalaya keeps its history in glaciers, rocks, sediments and river valleys. If we learn to read that history carefully, we may be better prepared for what the mountains will tell us next.

Warm regards

Mahesh G. Thakkar
Chief Editor

Editorial

CLIMATE CHANGE: A DEFINING ISSUE OF OUR TIME

CLIMATE change is no longer a distant warning for future generations; it is a present reality affecting millions of people across the world. It is also no longer a subject confined to scientific journals or international conferences. It has entered our everyday lives. Rising temperatures, erratic monsoons and unpredictable rainfall, prolonged heat waves, melting glaciers, floods, droughts and increasingly severe storms are clear signs that the Earth's climate is changing rapidly. The question before humanity is no longer whether climate change is real, but whether we have the collective will to respond to it.

The greatest irony of the climate crisis is that those who have contributed the least to global warming are often among those who suffer the most. Developing countries and vulnerable communities face serious threats to agriculture, water security, health and livelihoods. Farmers struggle with changing rainfall patterns, cities experience dangerous heat and flooding, and coastal communities face the growing threat of rising sea levels.

Human activity is at the heart of the problem. The excessive burning of coal, oil and gas, deforestation, rapid industrialisation and unsustainable patterns of consumption have increased the concentration of greenhouse gases in the atmosphere. Economic development is necessary, but development cannot be measured only by production and consumption. A truly sustainable economy must also protect the natural systems on which human life depends. Moreover, for decades, development has often been measured in terms of GDP, consumption and material



production. These indicators remain important, but they do not fully capture the health of ecosystems, the quality of life or the security of future generations. Economic progress that destroys the natural systems upon which the economy depends cannot ultimately be called sustainable progress.

Governments have a crucial responsibility. Strong climate policies, investment in renewable energy, cleaner transportation, energy efficiency, sustainable agriculture and protection of forests must become priorities rather than political promises. International cooperation is equally important because climate change respects no borders. Commitments made at international climate conferences must translate into measurable action on the ground. However, responsibility does not rest with governments alone. Businesses must adopt cleaner technologies and reduce emissions throughout their supply chains. Citizens, too, can contribute by reducing waste, conserving energy and water, using public transport where possible, and making more sustainable choices. Individual action cannot replace systemic change, but it can strengthen the social demand for it.

For countries like India, the challenge is particularly complex. India must continue its economic and social development while simultaneously reducing its environmental footprint and protecting vulnerable populations from climate-related risks. This requires innovation, investment and policies that combine economic growth with environmental sustainability. The climate crisis should not be viewed merely as an environmental issue. It is an economic, social, public-

health and moral issue as well. It concerns the kind of planet we will leave to future generations. Delaying action will only make the eventual cost higher, financially, socially and environmentally.

The good news is that humanity still has choices. Renewable energy, electric mobility, energy-efficient technologies, sustainable cities and nature-based solutions offer opportunities to build a cleaner and more resilient future. What is needed most is political courage, responsible citizenship and a willingness to think beyond short-term interests.

The Earth does not need another generation of promises. It needs action. Climate change is perhaps the defining challenge of our time, and history will judge us not by what we knew about the crisis, but by what we chose to do when we still had the opportunity to change course. The climate crisis is, at its core, a test of collective responsibility. No

individual, institution or country can resolve it alone. International cooperation remains essential, but global agreements will have little meaning without effective implementation at national and local levels. Climate change should, therefore, not be seen merely as a crisis to be managed. It is an opportunity to rethink how we produce, consume, govern and develop. The task before the present generation is not simply to protect the world they have inherited, but to build a more resilient, equitable and sustainable one.

I exhort all of you to please think over the climate crisis for a sustainable world for future generations.

Best wishes.....

Md. Firoze Quamar
Editor

From the Coordinating Editor's Desk

READING INDIA'S CLIMATE PAST TO PREPARE FOR ITS FUTURE: BSIP'S PALAEOSCIENCE AND THE ROAD TO CLIMATE RESILIENCE

CLIMATE change is no longer a distant concern. It is already being experienced through rising temperatures, changing rainfall patterns, droughts, floods, melting glaciers, shifting ecosystems and growing pressure on water and natural resources. Yet, to understand the changes we are witnessing today and what they may mean for India's future, looking only at the present is not enough. We also need to understand the climate history of the past.



80% of India's annual rainfall between June and September. Even relatively small changes in its timing, strength or distribution can, therefore, have far-reaching consequences.

This is where palaeoscience becomes important. By reading the natural records preserved in the Earth, scientists can reconstruct how India's climate and environment changed over hundreds, thousands and even millions of years. These records do not provide a simple blueprint for the future, but they

The Earth has been keeping its own climate archive for thousands, and in some cases millions, of years. That archive survives in lake sediments, pollen grains, tree rings, fossils, soils, rocks, glaciers, mangroves and other natural records. These archives preserve clues about periods when the monsoon strengthened or weakened, lakes expanded or disappeared, forests flourished or retreated, glaciers advanced or withdrew, and ecosystems and human societies responded to environmental change.

This long view has extraordinary value for India. The Indian Summer Monsoon is much more than a seasonal weather system. It is closely connected with agriculture, drinking water, groundwater recharge, rivers, ecosystems, food security, livelihoods and economic activity. The Intergovernmental Panel on Climate Change (IPCC), the United Nations body that assesses the science of climate change, estimates that the Indian summer monsoon contributes about

offer something modern observations alone cannot provide, a much longer perspective on climate variability and environmental change.

As the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, completes 80 years on 10th September, 2026, its scientific journey assumes particular strategic importance in the context of India's changing climate. From its historic foundation in palaeobotany, BSIP has evolved into a multidisciplinary centre for palaeosciences, with research spanning palaeoclimate, palaeoenvironment, palaeobiodiversity, palaeobiology, geology, geophysics, geochemistry and related fields.

Over these eight decades, its researchers have built a rich body of scientific evidence on the Indian monsoon, Himalayan climate, vegetation, forests, lakes, coastal environments and human-environment relationships. This long scientific legacy provides an important foundation for understanding India's

environmental and climate history and for applying lessons from the past to the challenges of the future.

The significance of this work extends beyond understanding what happened in the distant past. It provides valuable context for understanding the climate changes taking place today and for thinking about how India can prepare for those that lie ahead. If climate resilience is about making informed choices for the future, palaeoscience helps us understand the environmental history that brought us here and the range of changes that Earth systems have experienced before.

Why Palaeoscience Matters to Climate Policy

To the general public, palaeoscience may initially appear to be a science of fossils and ancient plants. In reality, its policy relevance is much broader.

BSIP brings together palaeobotany, geology, palaeobiology, geophysics, geochemistry and palaeogenomics to reconstruct environmental conditions across an extraordinary span of Earth's history, from billions of years ago to the recent past. This provides something that conventional instrumental observations cannot provide, and it is time depth.

Modern meteorological observations generally cover only a relatively short period compared with the timescales on which major climate systems operate. Palaeoclimate records can extend that observational window by centuries, millennia or millions of years.

The IPCC explicitly recognises this value. Its Sixth Assessment Report states that palaeoclimate studies provide essential context for understanding natural climate variability and the causes and consequences of climate change. They also help distinguish recent anthropogenic climate change from the background range of natural variability.

For India, that distinction is particularly important. A drought occurring today is not merely a weather event. Policymakers need to know whether its intensity falls within the historical range of natural variability, whether similar events have occurred before, how frequently they occurred, what environmental

conditions accompanied them, and how ecosystems and societies responded.

BSIP's palaeoclimate research helps build that missing historical baseline. For more than three decades, BSIP researchers have been reading India's climate archive, developing an impressive body of evidence on the Indian monsoon, Himalayan climate, coastal dynamics, tropical forests, vegetation change and human-environment relationships. Among the most important components of this work is the Quaternary Lake Drilling Project (QLDP).

The Indian Monsoon: A Climate Archive Written in Lake Sediments

Lake sediments may look like layers of mud, but scientifically they can function as natural climate archives. BSIP's work under the QLDP has generated high-resolution, multi-proxy records from the Central Ganga Plain, India's Core Monsoon Zone, northwestern India and other regions, extending in some locations back to approximately 15,000 years before present. These records reveal that the Indian Summer Monsoon has never been a static system.

During the Holocene, the approximately 11,700-year period following the last Ice Age, monsoon behaviour varied considerably over millennial and centennial timescales. Scientists have identified several periods when the Indian monsoon became weaker, including around 10,600, 9,600, 8,200, 6,000, 4,200, 2,800, 1,400 and 600 years ago. These repeated periods of weaker rainfall show that the Indian monsoon has naturally varied many times over thousands of years.

Among these, a particularly important period occurred around 4,200 years ago, when parts of the Indian subcontinent experienced a prolonged phase of drier conditions and a weaker monsoon. Evidence from lake deposits in Tamil Nadu, along with evidence of another dry period around 3,200 years ago, shows that major changes in monsoon rainfall affected lake water levels and surrounding ecosystems. These environmental changes also coincided with growing human activity, highlighting the complex relationship

between climate change, ecosystems and human societies. The significance is not merely historical.

The IPCC's assessment confirms that palaeoclimate evidence is important for understanding monsoon variability and for testing climate-model behaviour under different climate states. For India, this means that a 10,000- or 15,000-year climate record is not simply a story about the past. It can become a benchmark against which future climate projections are tested.

The 4,500-Year Tamil Nadu Record: Climate Lessons Beneath a Lake

One of the most compelling recent examples comes from Kondagai Lake in Sivaganga, Tamil Nadu.

A BSIP-led study analysed a sediment profile more than one metre deep and combined pollen, stable-isotope, grain-size and radiocarbon evidence to reconstruct approximately 4,500 years of changes in monsoon rainfall, vegetation, lake levels and flooding.

The study identified three important climatic phases, including the 4.2 ka arid event, a period around 4,200 years ago when conditions became significantly drier; the 3.2 ka dry phase, another period of reduced rainfall around 3,200 years ago; and the Roman Warm Period, a relatively warmer phase that occurred roughly 2,000 years ago. These environmental changes were linked to variations in monsoon strength, lake water levels and human activity. This type of research is particularly important for peninsular India, where long, well-dated multiproxy lake records are relatively limited.

Its policy message is clear. A long-term climate baseline can support drought preparedness, groundwater recharge planning, restoration of traditional tanks and wetlands, water budgeting, agricultural adaptation, ecosystem conservation and district-level climate-risk planning. For a drought-sensitive region, such as parts of Tamil Nadu, 4,500 years of environmental memory can become a valuable resource for planning the next few decades.

Majuli: Four Thousand Years of Climate, Floods and Human Vulnerability

The same principle becomes even more powerful in Assam. In June 2026, PIB reported a BSIP study reconstructing nearly 4,000 years of climate and vegetation history on Majuli, the world's largest inhabited river island.

Researchers recovered a 150-cm sediment core from Sakali Wetland and combined pollen analysis with grain-size studies to reconstruct vegetation, temperature, precipitation and river/flood dynamics. The record covers a period from approximately 4,040 to 500 years ago, providing a window into how the region's vegetation, climate and river systems changed over more than 3,500 years.

The study found that the region was initially warm and humid, followed by several periods of changes in monsoon rainfall and flooding. A relatively wetter period occurred during the Medieval Climatic Anomaly, a time when climate conditions changed noticeably across different parts of the world. During the last 500 years or so, the region became relatively cooler and drier, while human activities increasingly influenced the environment.

Majuli is not an abstract climate laboratory. It is home to communities confronting recurrent flooding, riverbank erosion, land loss and ecological change. Here palaeoscience acquires an immediate human dimension.

A 4,000-year environmental record can help answer a modern policy question. How has this landscape responded to climatic and hydrological stress before, and what can that history teach communities facing future risk?

This is exactly the kind of science that needs to travel from the laboratory to the district administration, disaster-management authority, water-resource department and community.

Trees as Climate Sensors: The Himalayan Record

Lake sediments are not the only archives. Trees also record environmental history through their annual growth rings.

BSIP scientists have used tree-ring records to reconstruct temperature and precipitation variability over centuries in the western and eastern Himalayas. A 694-year tree-ring rainfall reconstruction from Himachal Pradesh demonstrated that extreme droughts are recurrent features of the regional climate record. Earlier BSIP work has also documented significant precipitation variability in the western Himalayan monsoon-shadow region and changes in monsoon strength at high elevations.

The importance of understanding long-term Himalayan change is brought into sharp focus by the devastating 2026 disaster in Nepal, when a rapid slope failure involving glacier ice triggered a massive flow of ice, rock, mud and water, causing widespread destruction along the Trishuli River system. Such events highlight the growing need to understand how the Himalayan environment is changing and how climate, glaciers, water systems and fragile mountain landscapes interact. These records matter because the Himalaya is simultaneously a water tower, biodiversity reservoir and climate-risk hotspot.

For policymakers, long-term tree-ring records can provide valuable evidence for water-resource management, drought assessment, forest management, agricultural planning and natural-hazard preparedness. The policy opportunity is to move beyond viewing tree-ring science simply as a record of past climate and integrate it into regional climate-risk assessments and Himalayan adaptation planning, helping decision-makers understand long-term climate variability and prepare more effectively for future risks.

Coasts, Sea Level and Mangroves: Learning from Earlier Shorelines

India's climate vulnerability is not confined to the monsoon and Himalaya. Its long coastline is exposed

to sea-level rise, coastal flooding, erosion, salinity intrusion and ecosystem degradation.

BSIP research on how India's coastlines have changed over the past 11,700 years, including changes in coastline position, sea level and the growth and spread of mangrove forests, provides another important long-term perspective on India's environmental and climate history.

Studies of the Mahanadi Delta have shown how the growth and changes of mangrove forests have been influenced by climate and changes in sea level. Research in Gujarat and Kerala has also used different types of environmental evidence to understand how climate and sea levels changed from the period when the last Ice Age ended through the Holocene, the geological period covering the past 11,700 years.

Along the Tamil Nadu coast, researchers have examined how coastal communities and ecosystems have responded to environmental changes over time. This research is important because today's shoreline represents only one moment in a much longer history of coastal change. Understanding this history can help coastal planners identify areas vulnerable to flooding, protect and restore mangroves, plan climate-resilient infrastructure, support nature-based adaptation and better understand the range of shoreline changes that have occurred in the past. In simple terms, the coastline has a memory, and climate-resilient planning can benefit from learning how to read it.

When the Earth Was Warm: What 50 Million Years of Climate History Can Teach Us

Perhaps one of the most striking dimensions of BSIP's climate research comes from much deeper geological time. Scientists have investigated palaeoclimate conditions around 50 million years ago, when Earth was considerably warmer and atmospheric carbon dioxide concentrations exceeded 1,000 parts per million by volume (ppmv). In simple terms, CO₂ levels were more than twice as high as today's atmospheric concentration.

Using plant-based proxies, BSIP researchers reconstructed the climate of tropical land regions

near the equator and found evidence of high rainfall that helped sustain equatorial rainforests during this globally warm interval. This finding is scientifically important because it shows that a warmer Earth does not produce a single, uniform environmental response.

Temperature, rainfall, vegetation, atmospheric chemistry and ecosystem resilience interact in complex ways. Such deep-time records are valuable to modern climate science because they provide natural experiments that cannot be reproduced in a laboratory. They allow scientists to examine how the Earth system responded when temperature and atmospheric CO₂ were very different from today.

The Intergovernmental Panel on Climate Change (IPCC) also draws on evidence from past warm periods to improve understanding of carbon-cycle feedbacks, changes in the water cycle and the long-term sensitivity of the climate system.

For India's tropical forests and biodiversity-rich regions, this deep-time perspective raises an important question. How resilient will tropical ecosystems remain as greenhouse-gas concentrations and temperatures rise, and at what combination of heat and rainfall might ecosystems begin to cross thresholds of vulnerability?

The lesson from 50 million years ago is, therefore, not that the future will simply repeat the past. It is that Earth's climate system has responded to warming in complex ways before, and understanding those responses can help us better anticipate the range of changes that a warmer world may bring.

Climate Change Has Always Been About People Too

Climate is not only about temperature curves. It is also about food, settlement, migration, water and survival. BSIP's research into human-environment interactions and ancient agriculture provides this social dimension. Radiocarbon-dated carbonised seeds from Uren in Bihar, dated using the natural decay of carbon-14 to determine their age, provide evidence of agricultural intensification, trade and local adaptation from the Iron Age into the early medieval period.

Meanwhile, modern analogue datasets of fossil pollen and non-pollen palynomorphs from the Ganga Plain provide essential reference material for interpreting past vegetation and environmental change.

These studies remind us of an important principle for contemporary climate policy. Communities do not experience climate change in isolation; they experience it through agriculture, water, ecosystems, livelihoods and landscapes.

Recent Research Shows That the Archive Is Still Growing

BSIP's climate research is not only about the distant past. It is an active programme that continues to uncover new evidence about India's changing climate and environment.

The second phase of the Quaternary and Late Quaternary Dynamics Programme, is expanding detailed records of past climate and environmental changes from the Central Ganga Plain, Core Monsoon Zone and northwestern India. Scientists use multiproxy records, which means combining different clues, such as pollen, sediments and chemical evidence, to reconstruct past climate more accurately.

Recent studies include a 15,000-year record from Kanwar Wetland, climate reconstruction from India's Core Monsoon Zone since the Last Glacial Maximum, the coldest phase of the last Ice Age, and studies of tendu and palash to understand possible future changes in vegetation.

Pollen preserved in Raja Rani Lake, Chhattisgarh, indicates unusually strong monsoon conditions between 1060 and 1725 CE (Common Era, the same calendar system commonly used for modern dates). Together, these studies are steadily expanding our understanding of India's climate history and building a more detailed picture of how the country's climate has changed over time.

The Harappan Question: Climate, Monsoon and Civilisation

The relationship between climate and civilisation is particularly visible in BSIP's Himalayan palaeoecological research. A high-resolution pollen-based record from Deoria Tal in the Garhwal Himalaya has provided evidence of vegetation dynamics, hydroclimate change and Indian Summer Monsoon variability from the mid-Holocene to the present.

This research contributed to understanding the relationship between a weakened Indian Summer Monsoon and the contraction and eastward migration of populations associated with the Harappan civilisation between approximately 5,100 and 4,000 years ago. The lesson for the present is not that climate alone determines the fate of societies. Rather, it is that climate interacts with ecology, economy, water availability, technology and human decisions.

From Research to Policy: Making Palaeoclimate Knowledge Useful for India

The greatest opportunity now is to turn this valuable scientific record of India's climate past into useful information for policymaking. India is already working on climate change through several areas, including reducing emissions, adapting to changing climate, restoring ecosystems, preparing for disasters, securing water resources and promoting cleaner development. The next step is to ensure that knowledge of past climate changes becomes an important part of these efforts.

One important step would be to create a National Palaeoclimate Data Repository, bringing together valuable records from across the country. These could include lake sediments, pollen, tree rings, glacier records, coastal deposits, chemical evidence, fossil plants and environmental evidence from archaeological sites.

Bringing these records together would help scientists and policymakers better understand how India's climate has changed over hundreds and thousands of years. Such information could support

climate modelling, water management, ecosystem conservation, disaster preparedness and regional climate-risk planning.

It would also help India develop climate knowledge based on its own long-term environmental history, rather than depending mainly on climate information developed from global datasets.

Strengthening Climate Research Through Palaeoclimate Evidence

BSIP's research on tree rings, glaciers, ancient ecosystems and lake sediments can make an important contribution to India's climate research, particularly in areas, such as the Himalayan ecosystem, water security, climate adaptation and disaster preparedness. This work can complement ongoing climate research by other laboratories and scientific groups by adding something that modern observations alone cannot provide, a long-term record of how India's climate and environment have changed.

The future of climate science increasingly depends on bringing together present-day observations, evidence from the past, climate models, satellite observations, ecological studies and information about human societies. Within this broader effort, palaeoclimate research provides an important historical perspective that can help scientists better understand the range and nature of climate variability.

Palaeoclimate evidence also has an important role in the development and assessment of climate models. By providing information about climate conditions that existed in the past, these records give scientists an additional source of evidence for understanding how climate systems respond to changing conditions. This is particularly relevant for India, where monsoon behaviour, droughts, vegetation changes and water availability have varied considerably over long periods.

The significance of BSIP's work, therefore, extends beyond reconstructing the past. Its growing archive of environmental evidence can contribute to a broader scientific effort to understand how India's climate has changed, what factors have influenced those changes

and what this long-term knowledge can tell us about future climate risks.

BSIP and India's Place in the Global Climate Conversation

Climate change is a global challenge, but every region has its own climate story. For India, understanding that story in depth is important not only for national planning, but also for contributing to the global understanding of climate change.

BSIP's palaeoclimate research has a wider significance in this context. By studying evidence preserved in lake, sediments, tree rings, glaciers, soils and other natural archives, scientists can reconstruct how India's climate and environment changed over hundreds, thousands and even millions of years. These records provide valuable insights into monsoon behaviour, extreme climate events, ecosystem resilience, sea-level changes and long-term environmental variability.

This long-term perspective is relevant to the wider international climate-science effort, including scientific assessments by the IPCC and global climate discussions under the United Nations Framework Convention on Climate Change (UNFCCC) and the Conference of the Parties (COP).

The importance of this work goes beyond understanding India's past. India is a highly climate-sensitive region, with large populations and ecosystems dependent on the monsoon, rivers, forests, mountains and coastal environments. Its long environmental history, therefore, contains valuable evidence of how climate systems and ecosystems respond to changing conditions.

India has an opportunity not only to benefit from global climate knowledge, but also to contribute to it. BSIP's growing palaeoclimate archive can become an important part of this contribution by bringing evidence from the Indian landscape into the broader scientific understanding of climate change.

Understanding India's climate past can, therefore, help strengthen the scientific foundation on which

India engages with the global climate conversation and speaks with greater confidence about its climate future.

India's Climate Commitments and the Relevance of BSIP Research

India's climate commitments are becoming more ambitious, and understanding the science behind these goals is equally important. In its new Nationally Determined Contribution (NDC), submitted to the UNFCCC in April 2026, India has set targets for 2031–2035 that build on its earlier climate commitments.

India now aims to reduce the emissions intensity of its economy by 47% by 2035, compared with 2005 levels. In simple terms, this means producing economic output while releasing less greenhouse gas. India also aims to increase its carbon sink through forests and tree cover to 3.5 to 4 billion tonnes of CO₂-equivalent by 2035. A carbon sink is a natural system, such as a forest, that absorbs and stores carbon. In addition, 60% of the country's cumulative installed electricity capacity is targeted to come from non-fossil fuel sources by 2035.

These goals make it increasingly important to understand how India's forests, wetlands, mangroves, vegetation and water systems respond to changing climate conditions. This is where BSIP's research can make a valuable contribution. By studying natural records preserved in lakes, sediments, soils, pollen, tree rings and other archives, palaeoscience helps reveal how India's ecosystems responded to changes in rainfall, temperature, monsoon strength and water availability over thousands of years.

Palaeoscience does not determine India's future emissions pathway or how much carbon a forest can store. Its importance lies in providing the long-term environmental context needed to understand the natural systems on which climate action depends.

In simple terms, if India is planning its climate future, it also needs to understand how its natural systems have responded to climate change in the past. That long view can help make today's climate decisions more informed and future-ready.

From COP Statements to Local Climate Action

Climate discussions at the global level often revolve around tonnes of carbon dioxide, degrees of warming and national climate commitments. But for ordinary people, climate change is experienced in much more immediate and familiar ways.

For a farmer, it may mean that the timing of rainfall is becoming less predictable. For a village, it may mean increasing pressure on groundwater. In the Himalayas, communities may face changes in the availability of water. Along the coast, people may experience erosion and flooding, while wetland communities may see changes in water levels and seasonal flooding. For people who depend on forests, changing rainfall and temperature can also affect vegetation and the resources they rely on.

This is where BSIP's palaeoclimate research can help connect the global climate conversation with local realities. By showing how India's climate and ecosystems have changed over long periods, palaeoscience can provide valuable context for understanding present-day changes and planning for future risks.

The opportunity is to build a stronger connection between global climate assessments, national climate policy, state-level planning, district-level action and community resilience. Ultimately, climate science becomes most meaningful when knowledge about the past and projections of the future can help communities make better decisions today.

From Science to Society: Making India's Climate Knowledge Work

Climate change often reaches the public through alarming numbers: rising temperatures, extreme rainfall, droughts, floods, sea-level rise and increasing carbon dioxide. These numbers are important, but people understand climate change more deeply when they can connect it with real places, landscapes and stories.

This is where BSIP's palaeoclimate research has a special role to play. A pollen grain can reveal an ancient

monsoon. A tree ring can record years of drought. A layer of lake sediment can preserve thousands of years of environmental change. A mangrove deposit can tell the story of a changing coastline. These are not simply stories about the past. They can help us understand the environmental changes that shape India's future.

The challenge is to take this knowledge beyond scientific journals and make it accessible to citizens, teachers, students, journalists and decision-makers. Science communication through newspapers, radio, television, documentaries, podcasts, digital platforms, schools and universities can turn complex research into stories that people can understand and relate to.

Under Science Communication for Public Engagement and Partnership (SCoPE), BSIP is undertaking a range of initiatives to bring palaeoscience and climate science closer to society. These include *Palaeoscience Today*, a popular-science quarterly; *Kahani Dharti Ki* (Story of Earth), a weekly radio podcast with short audio-visual versions for social media; PRITHVI, the Palaeoclimate Film Festival of India and the National Dialogue on Earth Science Communication, a flagship initiative that connects palaeoscience with citizens through cinema and public engagement. SCoPE also supports capacity-building and skill-development workshops in science communication and ASPIRE, *Artful Science Communication to Popularise Impactful Research*, a programme designed to help research scholars communicate their research in engaging and accessible ways. Together, these initiatives create opportunities for scientists, research scholars, communicators, media professionals, students and other stakeholders to connect, share knowledge and explore creative and effective ways of communicating science to the public.

There is also a wider opportunity. Climate systems do not follow national boundaries. The Indian monsoon connects South Asia, while the Himalaya links water, glaciers, ecosystems and communities across countries. The Bay of Bengal connects coastal regions through shared climate risks. Greater scientific collaboration across the region could, therefore, help build a stronger understanding of shared climate challenges.

What should happen next is clear. India needs stronger efforts to bring together its palaeoclimate records, connect long-term environmental evidence with climate research, develop regional and district-level climate histories, strengthen research on the Himalaya and coasts, and make scientific findings more accessible to policymakers and the public. Greater international and regional collaboration can further expand this knowledge base.

India's climate future cannot be understood only through what is happening today. We also need to know what happened yesterday, centuries ago and thousands of years ago. BSIP's growing scientific

archive provides that long view. The opportunity now is to ensure that this knowledge travels from research laboratories to policy discussions, from scientific journals to newsrooms, and ultimately from science to society.

Because the real value of palaeoscience is not simply in telling us what happened in the past. Its greatest value lies in helping us prepare more wisely for the future.

Warm regards

Nimish Kapoor
Coordinating Editor

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India's Monsoon Has a Memory: Reading Climate Change in Lake Sediments

Anupam Sharma

Prologue

EVERY monsoon leaves a story behind, but not all of those stories are written in books or recorded by weather stations. Some are quietly preserved, layer after layer, at the bottom of India's lakes. These sediments hold clues to rainfall, temperature, vegetation and environmental changes that occurred thousands of years ago. By reading these natural archives, scientists can look beyond the instrumental records (of ~125 years) and reconstruct how the Indian monsoon has changed over centuries and millennia. Such knowledge is becoming increasingly important as India confronts a changing climate, growing weather extremes and an uncertain monsoon.

In this article, we will see the importance of Quaternary geology and the Lake Coring Initiative at the BSIP.

Introduction

The Quaternary Period, spanning the last 2.58 million years, is geologically the youngest chapter of Earth's history, yet it is arguably the most consequential for understanding the world we live in today. It encompasses the time of the evolution and human (*Homo sapiens*) dispersal, and the development of landscapes, river systems, and climate belts that we live in. Because it is the most recent and best-preserved interval in the geological record, Quaternary geology offers high-resolution, precisely dated archives of environmental change that can be directly compared with instrumental and historical records. These records can be used to predict the future climates as well.

The regional climate over the Indian subcontinent involves complex interactions of the atmosphere–ocean–land–cryosphere system on different space and time scales. In addition, there are evidence of anthropogenic activities influencing the regional climate in recent decades. Impacts associated with human-induced climate change, such as increasing heat extremes and changing monsoon patterns pose serious threats to lives and livelihoods on the subcontinent. As we are still agriculture based society, and the monsoon plays a pivotal role, hence, it is necessary to understand how and why the monsoonal climate is changing across India and how these changes are expected to evolve in the future.

Indian Monsoon

The distinct topographical and geographical features of the Indian subcontinent give the region widely varying climatic zones together with diverse vegetation groups that spread across the vast subcontinent. The Indian region is also prone to a wide range of severe weather events and climate extremes, including tropical cyclones, thunderstorms, heat waves, floods, droughts and many others. The frequency of extreme ISM events has increased in recent decades, and there is spatial heterogeneity in the occurrence of extreme events. However, such studies on extreme events are based on the instrumental records. Hence, longer high resolution palaeoclimate records are essential for understanding the monsoon variability on longer time scales as the Indian Summer Monsoon (ISM) also exhibits variations on different timescales ranging across sub-seasonal/intra-seasonal, inter-



Field work undertaken during 2021-2022 showing sediment trench sampling in Kanwar wetland, Begusarai District (Bihar), Indo-Gangetic plains.

annual (year-to-year), multi-decadal and centennial timescales, which are evident from instrumental records and paleoclimate reconstructions. Most of the studies related to the past climatic events are from the marine environment (mainly through ocean sediment cores), thus, we are trying to see the prominence of these events in the terrestrial environment (through lake sediments studies because the lakes act as sink) and whether they have caused any major impact on the society or not.

Indian monsoon and agriculture

Indian agriculture remains vulnerable to monsoon shocks. Over the years, the unpredictability of monsoon outcomes has, in fact, increased, which



Field work undertaken during 2023-2024 showing lake sediment coring of Surha Tal, officially known as the Jai Prakash Narayan Bird Sanctuary, is a natural oxbow lake and freshwater wetland located in the Ballia district of Uttar Pradesh, India.



Lake sediment coring at Bakhira Taal in Sant Kabir Nagar District of Uttar Pradesh, India.

challenges the accuracy of forecasting and further planning. States from the north and north- western parts, such as Punjab, Haryana, Himachal Pradesh, Jammu and Kashmir, Uttarakhand and Uttar Pradesh are important for the production of wheat and other rabi crops whereas the most important Kharif crop growing states are Assam, West Bengal, coastal regions of Odisha, Andhra Pradesh, Telangana, Tamil Nadu, Kerala and Maharashtra.

The SWM accounts for 75-80 per cent of the total rainfall that the country receives and is the mainstay of the kharif crop. Relatively, close co-movement is observed between rainfall intensity (expressed in terms of the deviation from normal) and sowing activity. The extent to which the soil moisture and reservoir gets replenished during the season also determines the prospects of the cropping seasons that follow.

Why lake archives

Lakes hold detailed sedimentary records of past changes in continental climate. These are particularly good recorders of climate variability because sediment from the surrounding environment accumulates in lakes, providing high-resolution histories of local environmental conditions in the past. Moreover, algae and other microorganisms produced within the lake (and its surrounding catchment area) can also be used as sensitive recorders of past environmental conditions of the lake, such as lake water chemistry, temperature and lake productivity. Lake sediments play an increasingly important role in the research of global and regional environmental evolution because they provide continuous environmental and seasonal information.

Quaternary Lake Drilling Program (QLDP) at the Birbal Sahni Institute of Palaeosciences (BSIP)

The Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, has initiated the Quaternary Lake Drilling Project with an aim to understand the monsoon behaviour in last several thousands of years, at least from Holocene (since 11,700 years ago to current time). As we know that instrumental climatic records (mainly the temperature, precipitation, relative humidity, air trajectory and so on) are maximum 150 to 100 years only are available with us, there is no choice left but to depend on proxy record (there are many biotic and abiotic proxies, such pollen and spores, diatoms, ostracods, palynofacies, etc. (all biotic) and sediment grain size, their bulk and clay mineralogy, geochemistry including stable isotopes, such as carbon, nitrogen, hydrogen, oxygen, sulphur, etc., organic biomarkers, such as alkanes, fatty acids, alkenones, etc. (all abiotic). As we know that climate by definition is a long-term phenomenon (average weather conditions of at least 30 years or more), large climatic records of at least a couple of thousands of years are essential for understanding the current climate and also to make climate predictions using climate modelling tools. Our study focuses on understanding Quaternary

climatic variability across India, in phased manner, we are currently focusing on the northern and Western India, to address the impact of monsoon variability on agriculture, ecology, and society. Leveraging high-resolution multi-proxy approaches, the research integrates sedimentary archives to reconstruct climate changes with implications for current and future monsoon behaviour in the face of anthropogenic climate change.

The investigation centres on lakes as sedimentary archives, which record detailed histories of past climatic conditions, offering insights into temperature, rainfall, and ecological dynamics. Previous paleoclimate records in the Indian subcontinent have shown inconsistencies, with different proxies suggesting contrasting climatic inferences. This highlights the



Sampling of tree-ring cores (*Tectona grandis*) from Maharajganj District, Uttar Pradesh, using an increment borer.

necessity for comprehensive long-term datasets to decode the variability of the ISM on multiple timescales.

The project by the Birbal Sahni Institute of Palaeosciences, an autonomous Institute under the Department of Science and Technology, Government of India, seeks to overcome gaps in current data through advanced techniques like radiocarbon and OSL dating, palynology, clay mineralogy, sedimentology, geochemistry including isotopes, environmental magnetism, and paleogenomics. The project aims to produce an integrated, validated dataset for hindcasting past climate scenarios and predicting future trends using climate, ecological, and social-ecological modelling.

The study's outcomes are expected to address scientific knowledge gaps and provide actionable insights into hydroclimatic variability, monsoon extremes, and their effects on agriculture, migration, and societal systems. Additionally, the project will enhance research capacity through academic training and foster collaboration between science, public policy, and conservation initiatives.

To establish better climatic records, our work also integrates the tree ring studies (Dendrochronology), which provides climate data on the yearly basis to calibrate the other proxies' data to make study more authentic.

The objectives of the project are:

- Quantitative reconstruction of high resolution spatio-temporal ISM variability using multi-proxy records
- Chronological lag and disparity in long term records
- Spatio-temporal mapping of abrupt and

extreme climate events including climate-culture interactions

- Ascertaining the causal mechanisms of climate vs vegetation & social response variables

Epilogue: Deliverables of the project

A high resolution, accurate, and a quantitative climatic record will be available through proxy data analyses, which will be helpful to derive a true and complete picture of the palaeo spatio-temporal hydro climatic variations within the Indian subcontinent and to address the scientific knowledge gaps. It will also help us to infer changes in the Climate, Ecology, Anthropogenic activities, Migratory pattern, and Archaeological settings, Epidemics, Agriculture and Pollution, etc.

Also, this program will motivate and produce research students (PhD and Postdoctoral) and research training will be imparted for dissertation students at the graduate and postgraduate level through different research topics.

This project shall also enable BSIP to serve as a national repository for Lake cores and also an R&D and training centre for lake studies in India. All this shall be part of the capacity building for climate change research in India.

This flagship project of the BSIP shall serve as an interface for public outreach, policymakers, management, conservation, and consultancy too. Further, it will provide credible information on Indian subcontinent climate system and used by all stakeholders involved directly or indirectly on the global scale and generate skilled human resource for climate research programs.

About author



Dr Anupam Sharma is Scientist G at the BSIP, Lucknow. His research interest include the understanding of earth surface processes, Quaternary palaeoclimate & provenance characterization using geochemistry, mineralogy, and isotope systematic, understanding tectonics and seismicity in light of geochemistry and mineralogy, soil formation and nutrient dynamics including soil pollution and remedial strategies, rock/desert varnish study: coupling geochemistry, electrochemistry and astrobiology and geochemical characterization of radiogenic waste.

Pollen Grains Tell the Tale of Why the Harappan Civilization Shrank: Signature of the Abrupt Climate Change (ACC) Event (the '4.2 ka event') from the Garhwal Himalaya, India

Mohammad Firoze Quamar

CLIMATE change is a defining issue of our time and the various records (e.g. geological, biological, glaciological, historical and archaeological) contain abundant evidence of the ways in which Earth's climate has changed in the past that are also highly relevant in understanding how it may change in the future. In the history of Earth, the Quaternary is of critical significance due to frequent and rapid climatic changes and to understand these changes, the palaeoclimatologists have emphasized the importance of deciphering the past climate with the use of various proxy records viz., pollen, geochemical, diatoms, charcoals, etc. retrieved through the analysis of sediments from oceans, lakes and swamps, which serve as natural archives. Pollen grains preserved in a variety of settings, particularly anaerobic sediments (lake, swamp, peat, etc.), provide a wealth of information about their source's vegetation and environment. Climate change is most evidently reflected in the vegetation because the vegetation of any area is an integral and basic composition of the ecosystem, which is sensitive to and governed by the climatic changes. The distribution pattern of vegetation strongly depends on the climatic conditions (precipitation, temperature), soil characteristic and altitude, as well as human and natural impacts (Chen et al., 2006; Faegri and Iversen, 1964; Gasse et al., 1991; Ivanov et al., 2007; Kar and Quamar, 2019, 2020; Sun and Wu,

1987; and references cited therein). The influence of climate on vegetation is so great that each climatic zone has its own characteristic vegetation type. Therefore, plants are among the best indicators of environmental and climatic changes, both temporally and spatially.

Abrupt Climate Change (ACC), also known as Rapid Climate Changes (RCC), which take place over a few decades to a few hundred years ago (BP: Before Present), during the Holocene (since 11, 700 years to the present) are a potential goldmine of information for understanding tipping points in the climate system (Liu et al., 2014; Park et al., 2019; Scroxton and McKay, 2024). The ACC events also pose a critical risk to ecosystems and human lives.

Pollen analysis of a 3.80-m-long well-dated (10 AMS ^{14}C dates) sediment core, comprising 55 pollen samples, from Deoria Tal (30.5222° N; 79.1277° E; 2393 m a.s.l.) Garhwal Himalaya, India, provide a 5200 year high resolution (centennial-to millennial-scale) record of vegetation history and variations in the Indian Summer Monsoon (ISM) (Figures 1-6). The study demonstrates that a *Pinus*-dominated broad-leaved/conifer forest surrounded the site between ~5200 and 4000 cal yr BP, reflecting the influence of a cool, dry climate and a moderate ISM for much of this interval. Shifts in the relative abundance of the dominant arboreal taxa (*Pinus*, *Quercus*, *Aesculus*), and non-arboreal taxa, including terrestrial herbs and

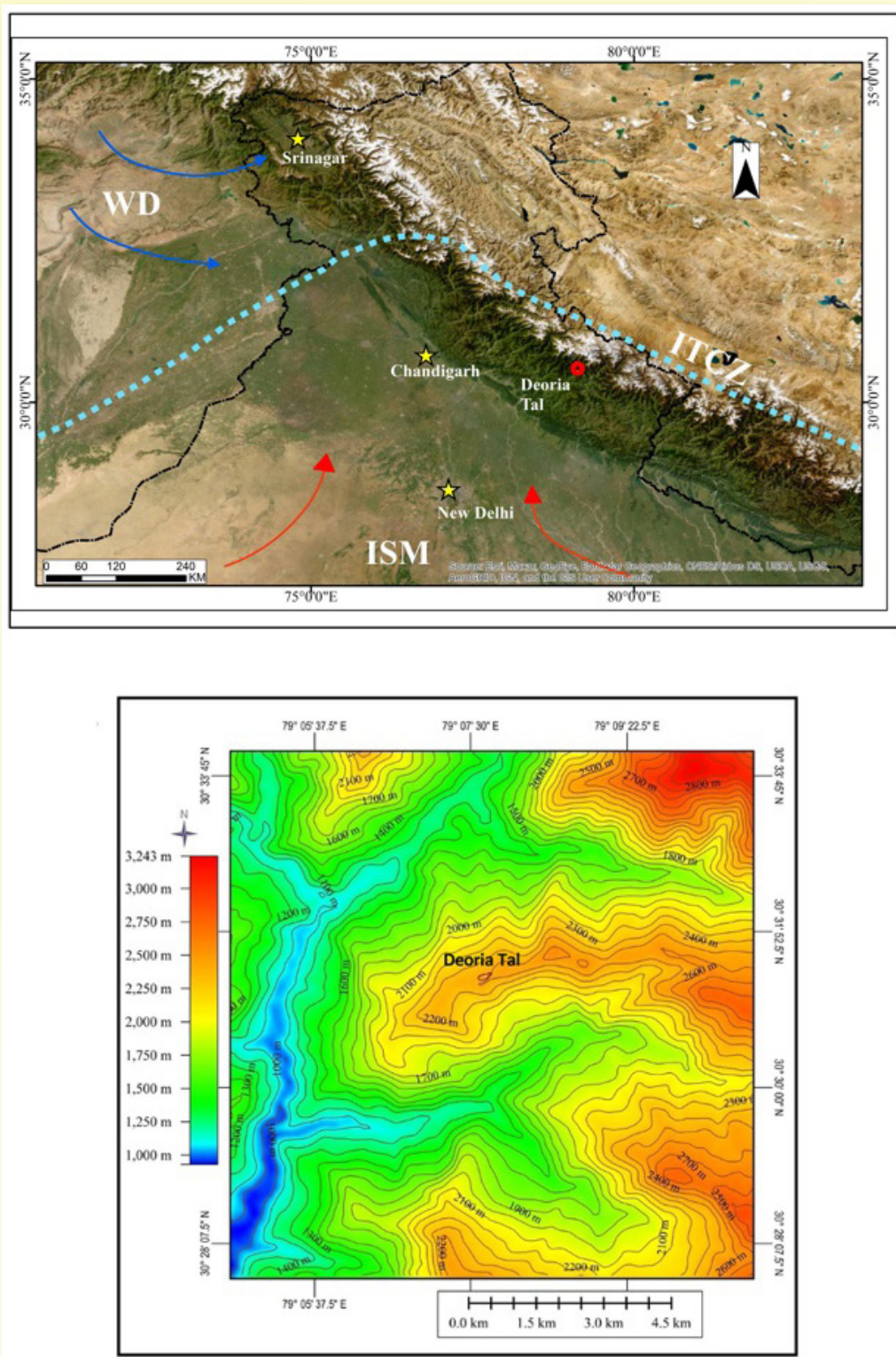


Figure 1. Map of the study area with the study site, Deoria Tal, highlighted. Upper panel provides national context, including the location of New Delhi, Chandigarh and Srinagar. Lower panel depicts the local topography surrounding the study site.

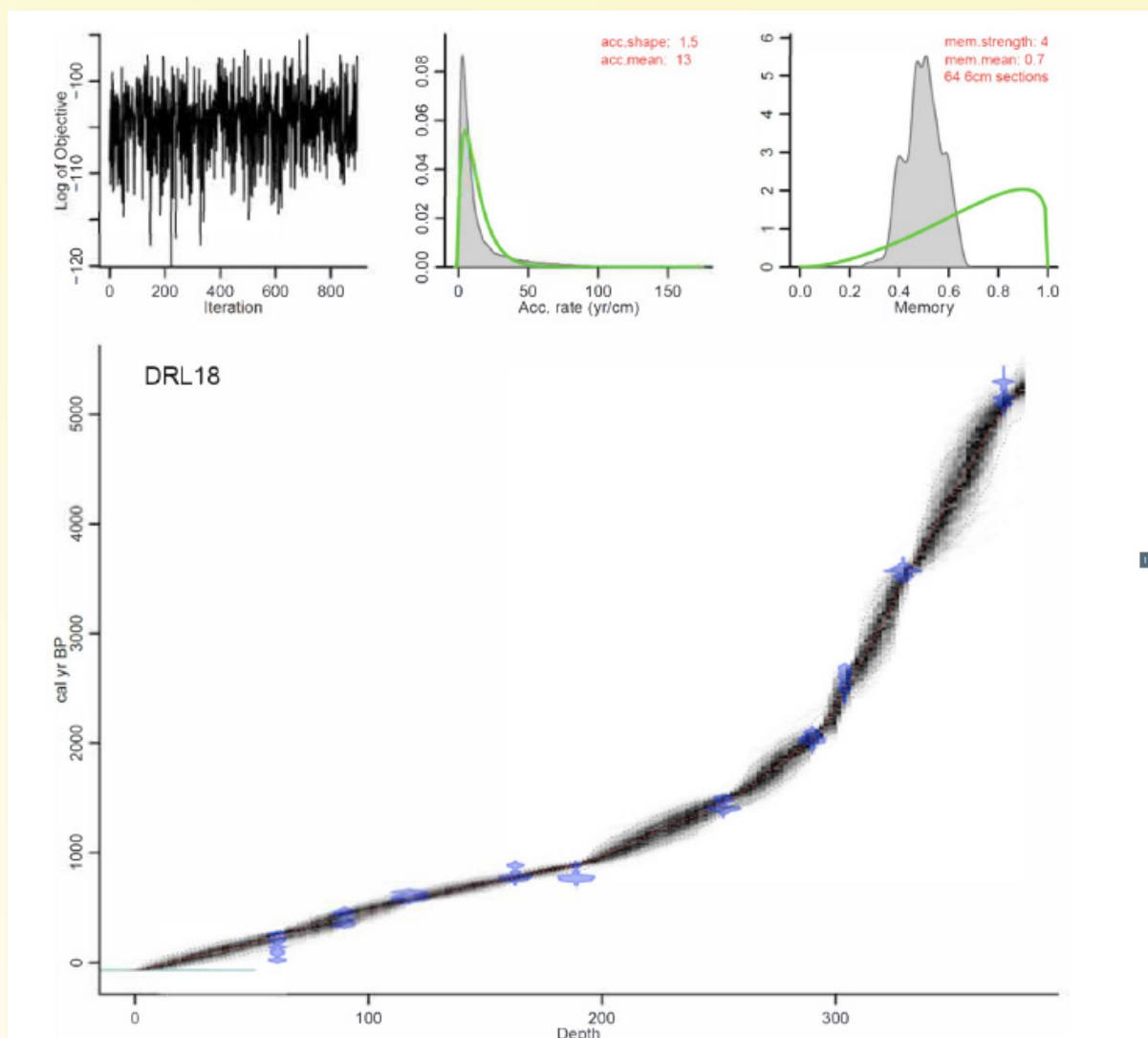


Figure 2. Age-depth model for Deoria Tal, developed using the BACON (Blaauw and Christen, 2011). The depth of the lake sediment core (x-axis) is plotted from 0 to 380 cm and the calibrated ages (y-axis) are plotted in cal yr BP. The water chestnut (*Trapa*) seed cases (blue) are plotted against the age-depth curve (black) with the dotted lines marking the 2σ range of uncertainty.

pteridophytic and marshy taxa, suggest that the interval between 4400 and 4000 cal yr BP was characterized by a highly variable ISM. A notable, abrupt increase in the Oak/Pine ratio evident at ~4250 cal yr BP corresponds with previously documented elemental and sedimentological evidence from the site of an abrupt, short-lived climate event at 4200 cal yr BP, which is globally known as the “4.2 ka event” (ka= thousand years ago: BP- Before Present, where Present is 1950 CE). The cool-dry climate and weak ISM could

be ascribed to the southward shift of the Inter tropical Convergence Zone (ITCZ), which occurs in response to the decreasing summer insolation in the Northern Hemisphere. The abrupt weakening of the ISM at 4.2 kr BP could be linked to the stronger phase of El-Niño and a shift of the Indian Ocean Dipole (IOD) to a strong negative state (Morrill et al., 2003; MacDonald, 2011). This abrupt reduction in the ISM at 4.2 ka had significant societal impact, resulting into the migration of population residing along the Indus River and the

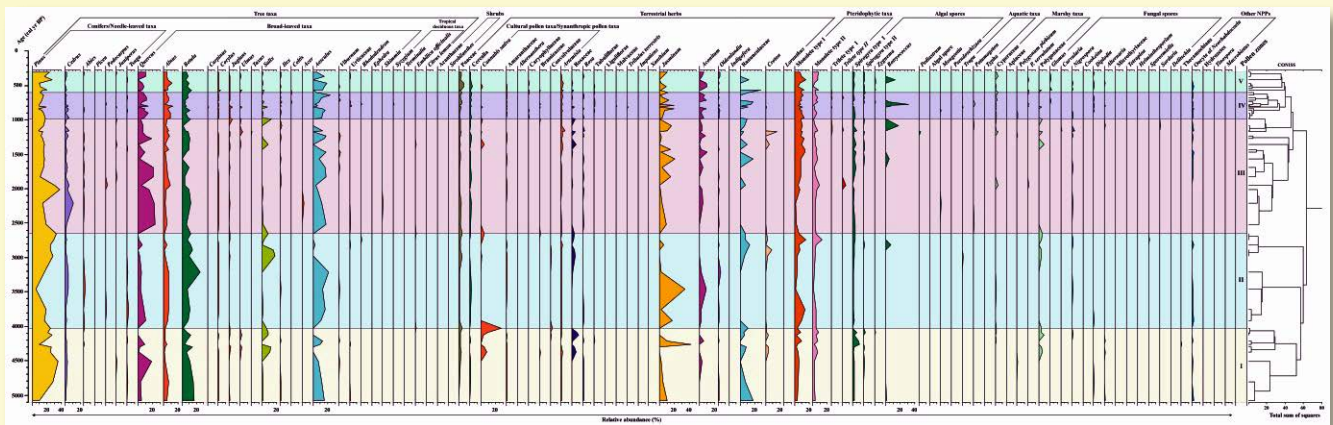


Figure 3. Pollen diagram of Deoria Tal (Lake) sediment core, Garhwal Himalaya (Uttarakhand), India.

Ghaggar-Hakra River (by 4200 cal yr BP; Pant, 2003; Puri, 2008) of Indus Valley Civilization (Harappan Civilization) to new areas to the east (Ganga Plains) for domestic and agricultural use, as reliable seasonal flooding of the river system around the edge of the Thar desert disappeared (Giosan et al., 2012). The demographic and spatial contraction of the Harappan Civilization (between 4300 and 3900 cal yr BP) and other civilizations to the west coincided with the ACC event centered at ~4.2 ka (Staubwasser et al., 2003; Staubwasser and Weiss, 2006). As one of the most pronounced Holocene cooling events, this ACC or RCC event (i.e. the 4.2 ka event) provides a natural experiment to investigate the teleconnections between the ISM, as well as various forcing factors, such as the El Niño, Inter Tropical Convergence Zone (ITCZ), Indian Ocean Dipole (IOD), and Summer Insolation (SI) in the low-latitude region.

The study further suggested that between ~4000 and 2650 cal yr BP the density of the *Pinus*-dominated broad-leaved/conifer forest increased, suggesting the site was influenced by a warmer, wetter climate, particularly between 4000 and 3200 cal yr BP. Between ~2600 and 1000 cal yr BP, mixed (temperate) broad-leaved /conifer forest expanded in response to a warm and moist climate, as evidenced by increases in *Quercus* and aquatic and marsh taxa, reflecting an extended interval of a strengthened ISM, which coincides with the global Roman Warm Period (RWP), also known as the Roman Climate Optimum (RCO) (Figures

7 & 8). The high rainfall during the RWP occurs contemporaneously with increased solar insolation and the associated northward shift of the Inter Tropical Convergence Zone (ITCZ) (Haug et al. 2001; Solanki et al. 2004). The RWP has been described as an interval when the circum-North Atlantic region was warm, triggered either by solar variability or internal North Atlantic variability (Martín-Puertas et al. 2009; Büntgen et al. 2011). Importantly, the RWP coincides with the rise of the Maurya Empire in India (Singh 2008). The existence of a strong ISM during the RWP boosted agricultural production and socioeconomic development in India (Gupta et al., 2006; McCormick et al., 2012; Singh, 2008). Agricultural expansion and the existence of a trade surplus during the RWP, facilitated the development of a thriving and robust economy in India, leading to this interval being described as the ‘Golden Age of India’ (McCrindle 1877; Singh et al. 2020).

The interval between ~1000 and 600 cal yr BP (~ 950–1350 CE) was characterized by a fluctuations in the density of the mixed (temperate) broad-leaved/conifer forest, likely reflecting the influence of a moderately strong ISM, followed by a progressively weakening ISM, particularly after ~800 cal yr BP. The timing of the phase of increased ISM precipitation broadly coincides with the Medieval Climate Anomaly (MCA) (Figures 7 & 8). The ISM intensification during the MCA could be attributed to the northward shift of the ITCZ (Haug et al., 2001; Rehfeld et al.,

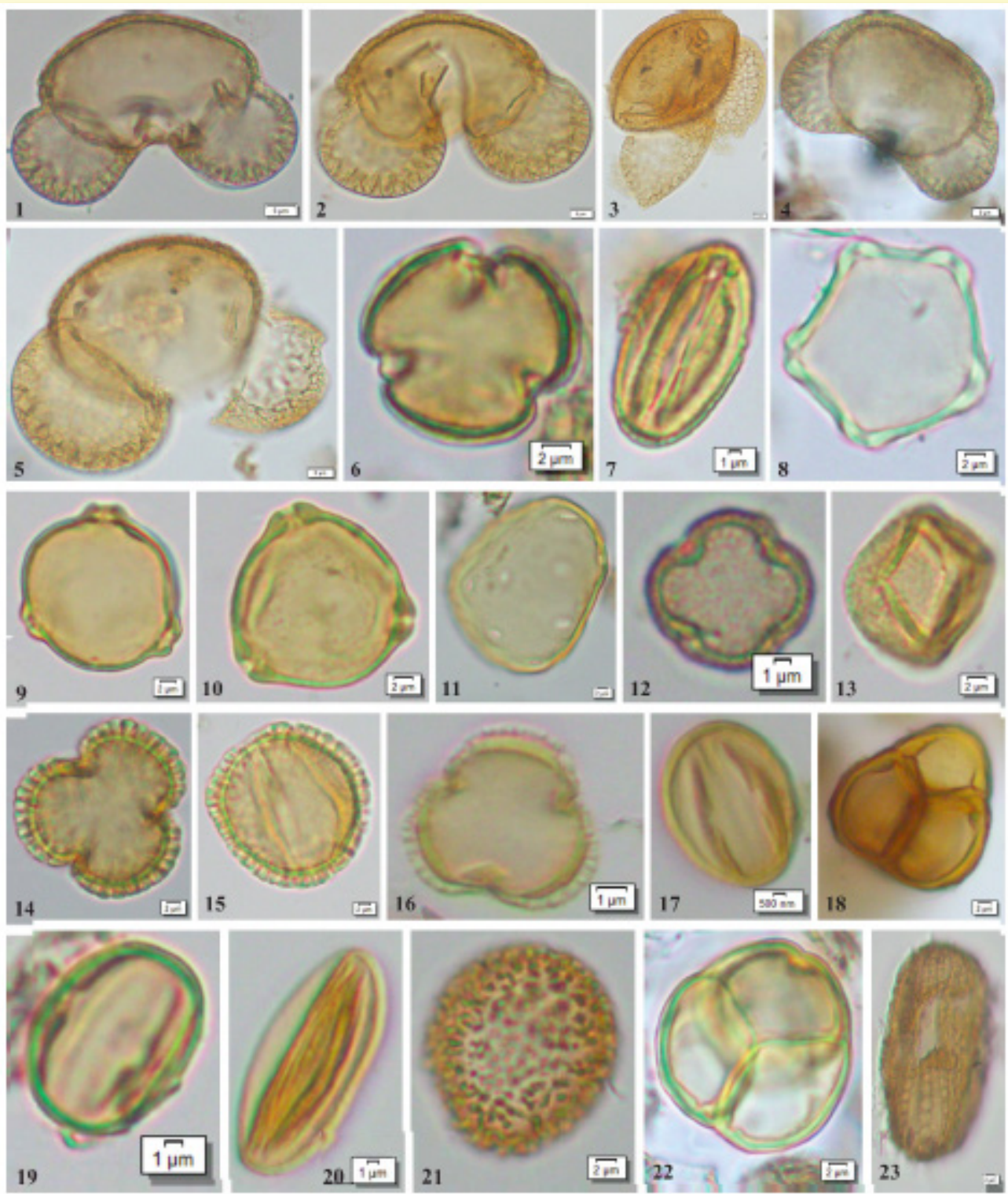


Figure 4. Key palynomorphs recovered from the DRL sedimentary core samples. 1. *Pinus*, 2. *Cedrus*, 3. *Abies*, 4. *Picea*, 5. *Podocarpus*, 6 & 7. *Quercus*. 8. *Alnus*, 9. *Betula*, 10. *Corylus*, 11. *Juglans*, 12. *Salix*, 13. *Aesculus*, 14–16. & *Ilex*, 17. *Skimmia*, 18. *Rhododendron*, 19. *Terminalia*, 20. *Ephedra*, 21. *Croton*, 22. *Rosa*, 23. *Strobilanthes*.

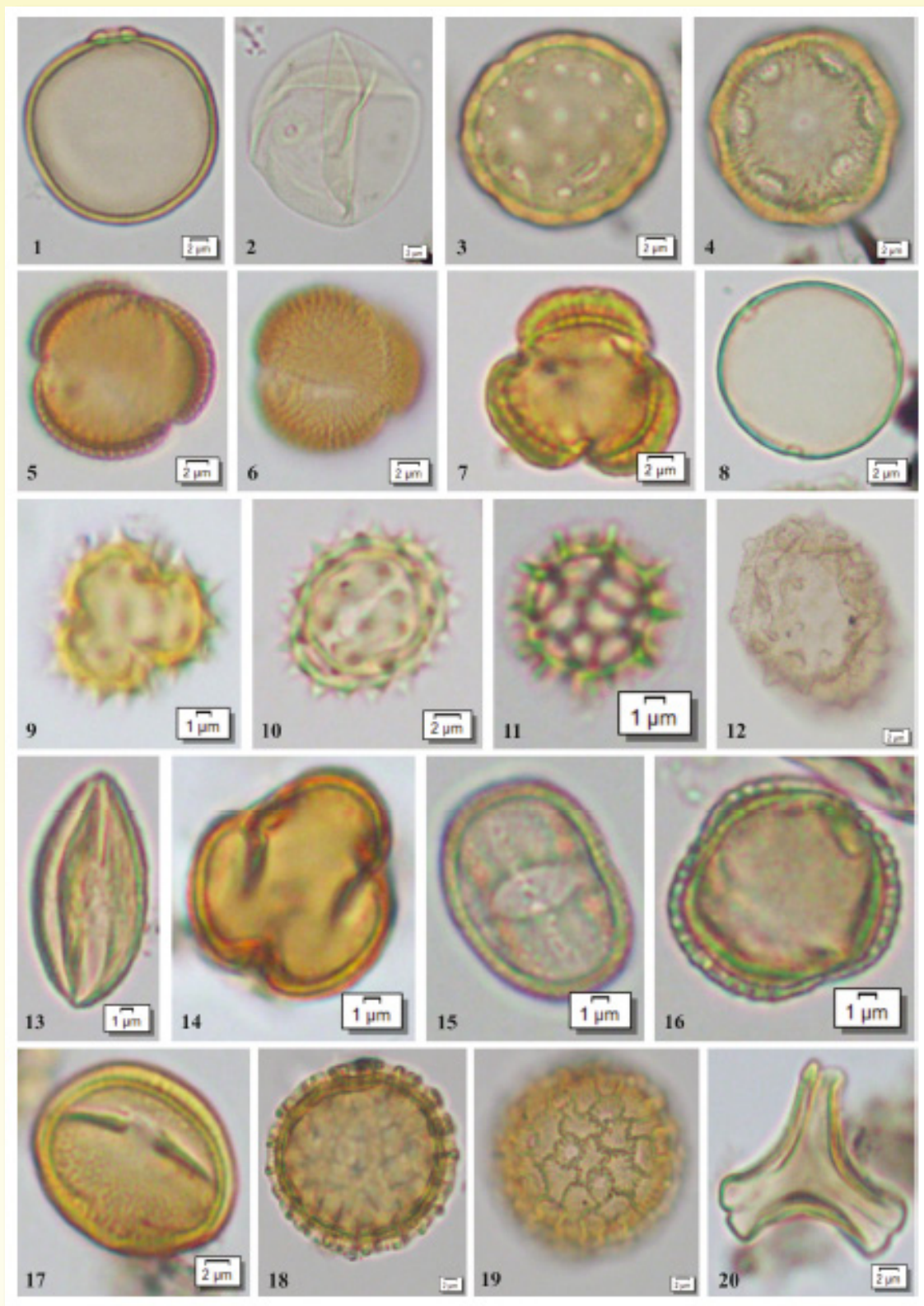


Figure 5. 1. Poaceae, 2. Cerealia, 3. Amaranthaceae, 4. Caryophyllaceae, 5 & 6. Brassicaceae, 7. *Artemisia*, 8. *Cannabis sativa*, 9 & 10. Asteroideae, 11. Cichorioideae, 12. Malvaceae, 13. Rosaceae, 14. *Aconitum*, 15 & 16. *Viburnum*, 17. *Oldenlandia*, 18 & 19. *Jasminum*, 20. *Loranthus* (*Dendrophthoe falcata*).

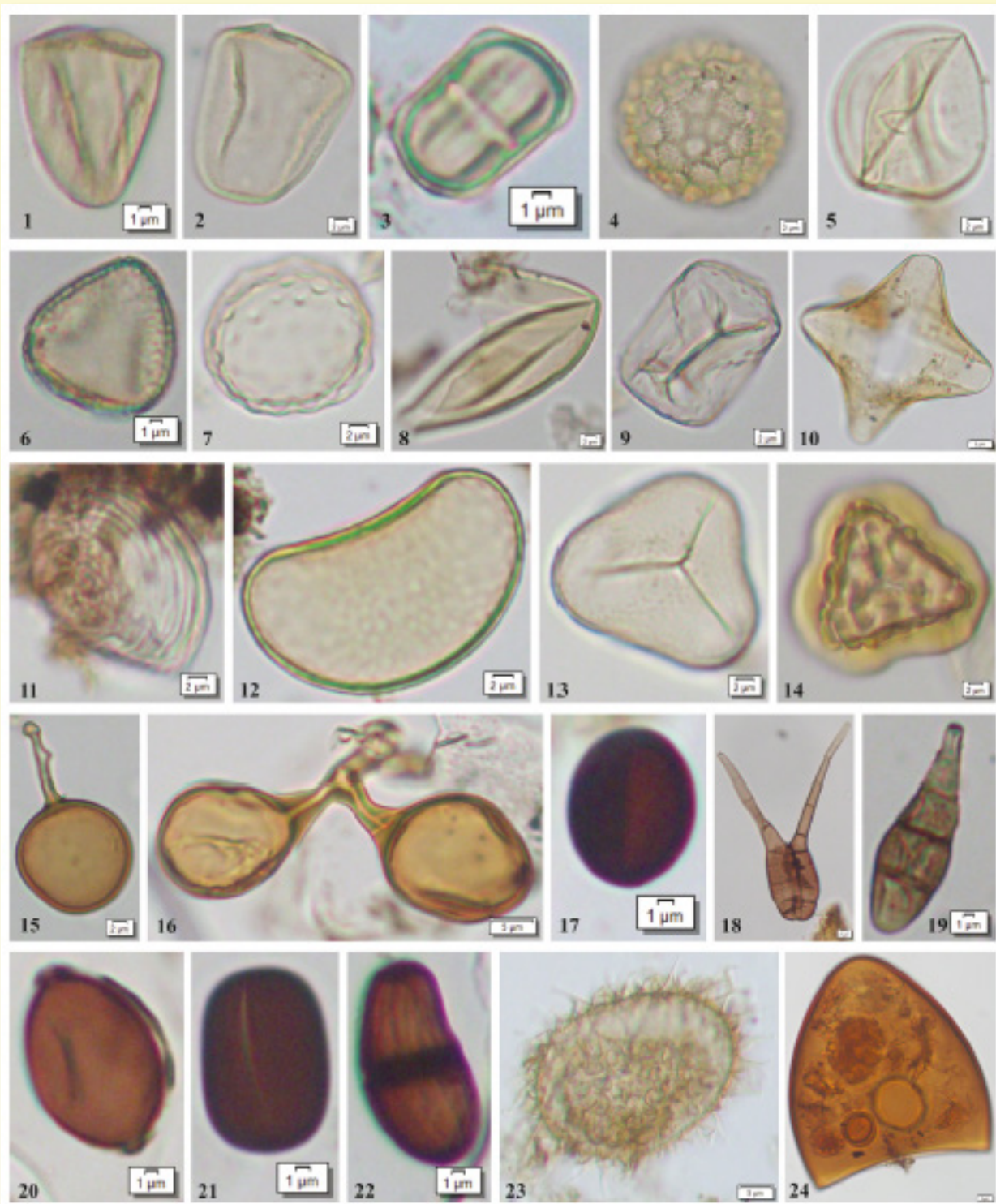


Figure 6. 1 & 2. Cyperaceae, 3. *Polygonum plebeium*, 4. *Polygonum serrulatum*, 5. *Potamogeton*, 6. *Typha*, 7. *Zygnema* (zygospores), 8 & 9. *Spirogyra* (zygospores), 10. *Mougeotia*, 11. *Pseudoschizea*, 12. Monolete fern spore I, 13. Trilete fern spore I, 14. Trilete fern spore II, 15 & 16. *Glomus*, 17. *Nigrospora*, 18. *Tetraploa*, 19. *Alternaria*, 20. *Sordaria*, 21. *Sporormiella*, 22. *Cookeina*, 23. *Hydrozetes* (Oribatae, Acari), 24. Oocyte of *Neorhabdocoela* (possibly *Microdelyellia armigera*).

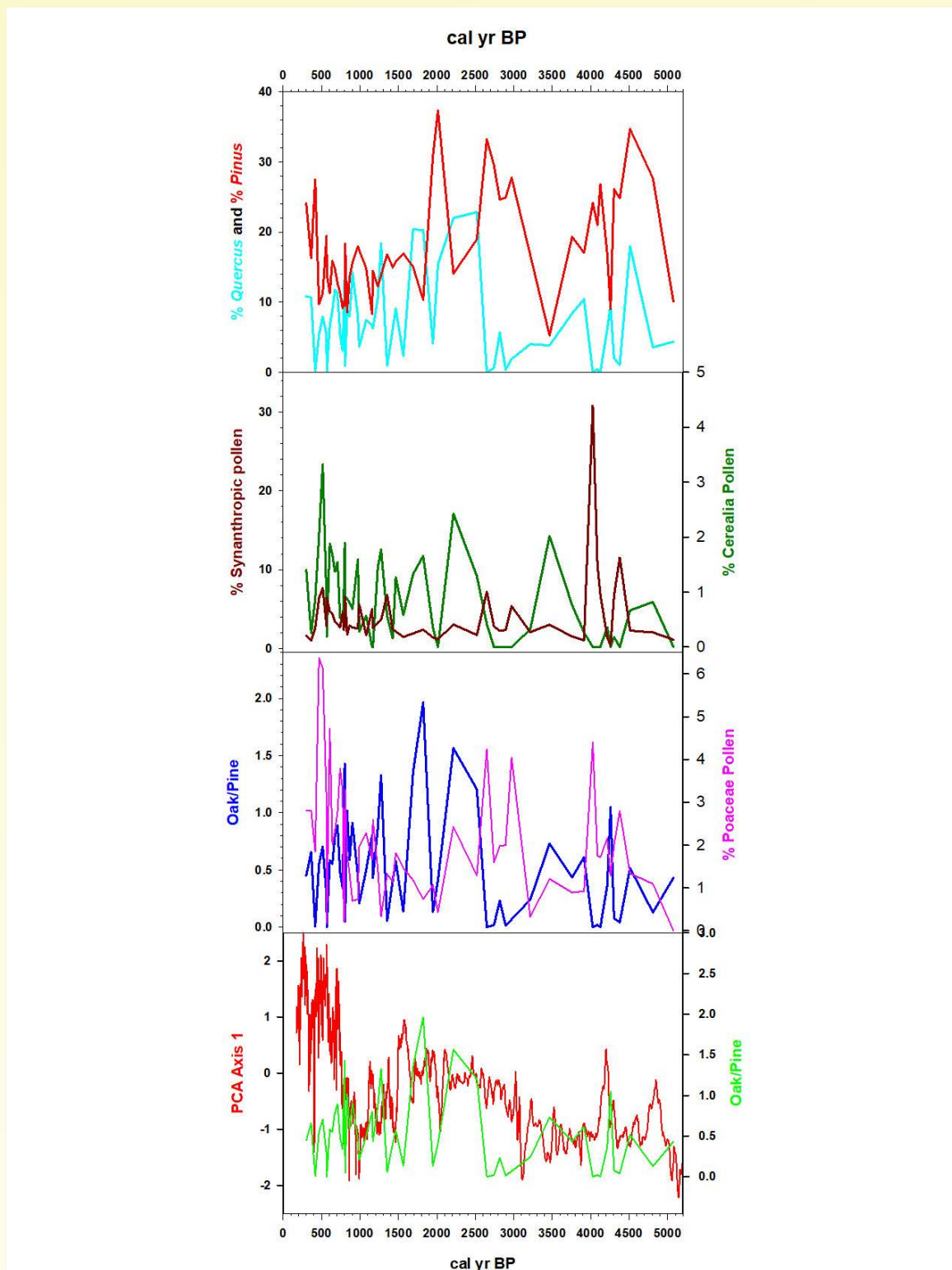


Figure 7. A) Relative abundance of *Quercus* and *Pinus* plotted against time. B) Relative abundance of synanthropic pollen taxa, comprised of *Artemisia* and *Cannabis sativa*, Amaranthaceae, Brassicaceae, *Alternanthera*, Caryophyllaceae and Convolvulaceae, and relative abundance of *Cerealia*. C) Oak/Pine pollen ratio and relative abundance of *Poaceae*. D) Oak/Pine pollen ratio and PCA Axis 1 scores of XRF-derived elemental data (Niederman et al., 2021).

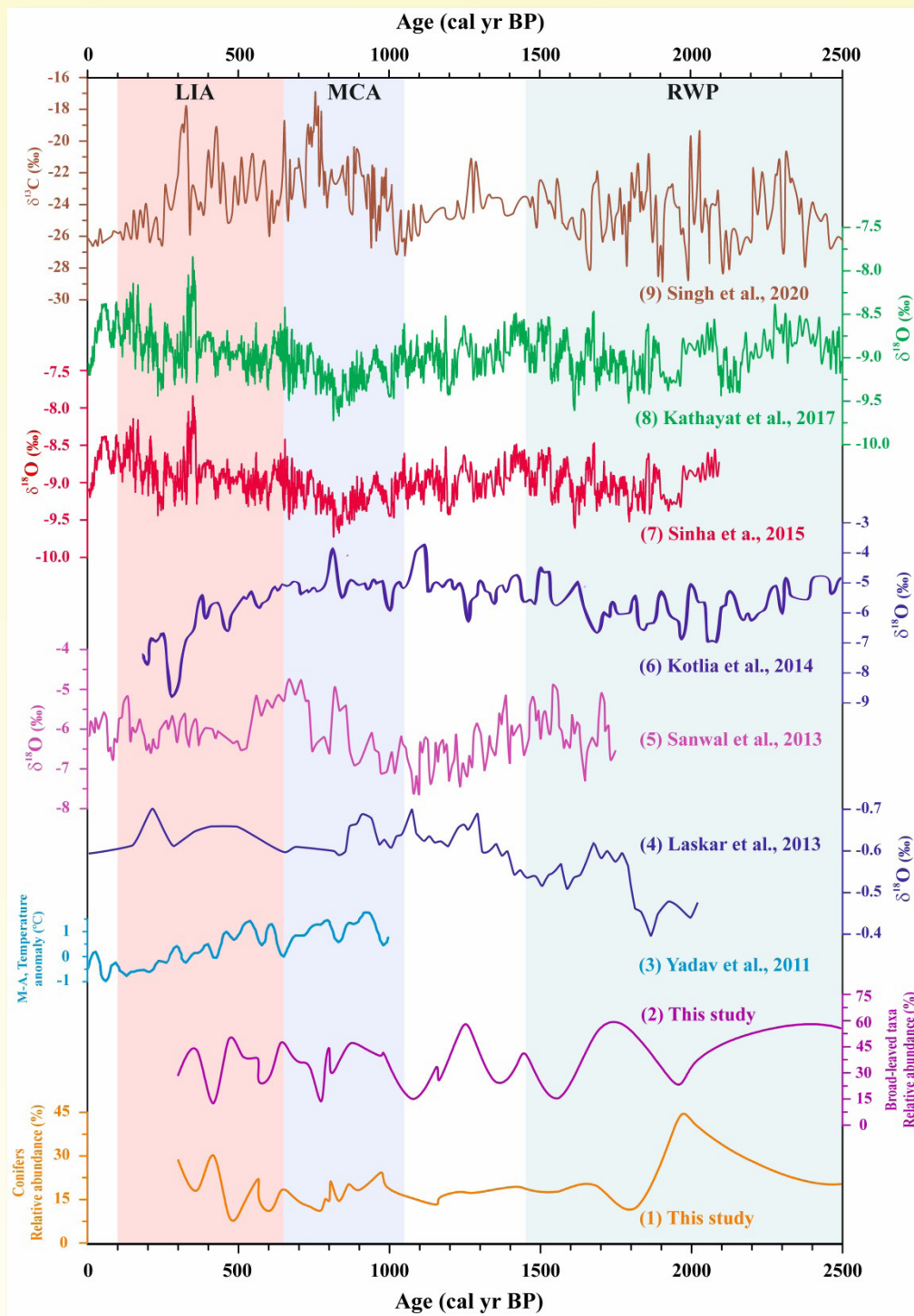


Figure 8. Correlation of the Deoria Tal pollen record with the existing palaeoclimate records, with reference to the global climate events, such as Roman Warm Period (RWP), Medieval Climate Anomaly (MCA) and Little Ice Age (LIA). (1 and 2: This study); (3). Yadav et al. (2011) from Himachal Pradesh; (4). Laskar et al. (2013) from the Andman and Nicobar Islands; (5). Sanwal et al. (2013) from Kumaun; Lesser Himalaya; (6). Sinha et al. (2015) speleothem $\delta^{18}\text{O}$ record of the Sahiya Cave; Uttarakhand; Lesser Himalaya; (7). Kathayat et al. (2017) speleothem $\delta^{18}\text{O}$ record of the Sahiya Cave; Uttarakhand; (8). Singh et al. (2020) from Rewalsar Lake, Himachal Pradesh, NW Himalaya.

2013); however, factors such as volcanic aerosols and solar variability have also been invoked to explain the MCA (Bradley et al. 2016). Other factors that have been identified as potential contributors to the MCA include changes in the strength of the thermohaline circulation in the North Atlantic (Cronin et al. 2003), fluctuations in ENSO-modulated solar insolation (Emile-Geay et al. 2007), positive temperature anomalies, increased sunspot activity, and high solar radiation (Gupta et al. 2005). Additionally, it has been noted that enhanced wind strength in the Arabian Sea and wetter conditions over India coincided with this period (Haug et al., 2001; Gupta et al., 2003; Solanki et al., 2004; Mann et al., 2008).

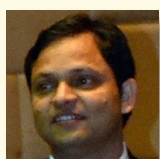
Finally, between ~600 and 300 cal yr BP (~1350–1650 CE), a reversion to a *Pinus*-dominated mixed broad-leaved/conifer forest suggests that this interval, which correlates with the Little Ice Age (LIA; 1550–1850 CE), was characterized by a reduction in the strength of the ISM (Figures 7 & 8). The weak ISM during the LIA may be linked to an intensification of the Asian westerly jet stream and Westerlies over the Middle East during a positive phase of the North Atlantic Oscillation (NAO) and the migration of the Asian jet to the lower latitudes during the warm phase of ENSO (Dixit and Tandon, 2016). The weakest phase of the ISM across the Indian subcontinent during the past three millennia and also during the

LIA can be related to the southward shift of the ITCZ owing to increased northward energy flux across the equator during a cold northern hemisphere (Singh et al., 2020; Dutt et al., 2018; Bischoff and Schneider, 2014; Kathayat et al., 2017; Prasad et al., 1997; Laskar et al., 2013; Rawat et al., 2015; Das et al., 2017). ENSO restricts the northward movement of the ITCZ that delays the onset of the summer monsoon causing a reduction in the rainfall (Sinha et al., 2011). Dutt et al. (2021) suggested that the low rainfall during the LIA largely impacted the agricultural production and, in turn, the economy of the Indian subcontinent. Maharatna (1996), Cook et al. (2010) and Mishra et al. (2019) pointed out that the 12 major famines during the era of British rule in India (1765–1947) caused the deaths of millions of people were a result of the failure of the South West Monsoon (SWM/ISM), which led to widespread droughts and crop failures (Quamar, 2022b).

Reference

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About author



Dr Mohammad Firoze Quamar is Senior Scientist at BSIP, Lucknow. His research interests mainly include the reconstruction of ISM-driven vegetation dynamics and contemporary climate change during the late Quaternary in the CMZ of India, as well as in the Himalaya, Western Ghats and Western India. He also takes keen interest in studying Non-Pollen Palynomorphs (NPPs), especially the Spores of Coprophilous Fungi (SCF), as well as in aerobiology and melissopalynology.

A Climate Story Written in Pollen: 13,000 Years of Vegetation Change in the High Sikkim Himalaya

Jyotsna Dubey

A climate story preserved in microscopic pollen grains

THE Himalaya may look permanent and unchanging when viewed from a distance, but its forests have never been static. Over thousands of years, changing temperature, rainfall and monsoon behaviour have repeatedly reshaped the vegetation of this vast mountain system.

Evidence for these changes is preserved in microscopic grains of pollen buried deep within the sediments. Every flowering plant produces pollen, and most of these tiny grains eventually settle in lakes, wetlands and other depositional environments. Layer after layer, they become incorporated into sediments. With time, older material is buried beneath younger deposits, creating a natural archive of environmental change. By recovering these sediments and examining their pollen under a microscope, scientists can reconstruct aspects of vegetation history stretching far beyond the period covered by instrumental climate observations.

This approach forms the basis of a recent study which used a pollen record from the higher Sikkim Himalaya to examine vegetation diversity and its relationship with monsoonal variability over approximately the last 13,000 years. The study provides a long-term perspective on how Himalayan vegetation expanded, diversified, declined and recovered as environmental conditions changed.

Reading the past through pollen

Pollen is remarkably useful as a palaeoenvironmental indicator, but it must be interpreted carefully. A pollen grain represents a plant that produced it, but the amount of pollen preserved in sediment does not necessarily correspond directly to the abundance of that plant in the surrounding vegetation.

Plants differ greatly in the amount of pollen they produce. Some pollen grains can travel considerable distances, while others remain close to their source. Sediment type, water movement and preservation can also influence which grains ultimately become part of the fossil record. Therefore, a pollen assemblage is not a simple photograph of the vegetation growing around a site.

For this reason, Dubey et al. looked beyond individual pollen taxa and considered broader characteristics of the assemblage, including total pollen abundance, pollen richness and alpha diversity in the Eastern Himalaya (Figures 1 & 2). Together, these measures provide a more meaningful picture of how the vegetation community changed through time.

From a changing landscape to expanding forests

The record begins around 13,000 years ago, during the transition from the Late Pleistocene into the Holocene. This was a period of major environmental adjustment following the last major glacial phase. Climate was changing, landscapes were reorganising

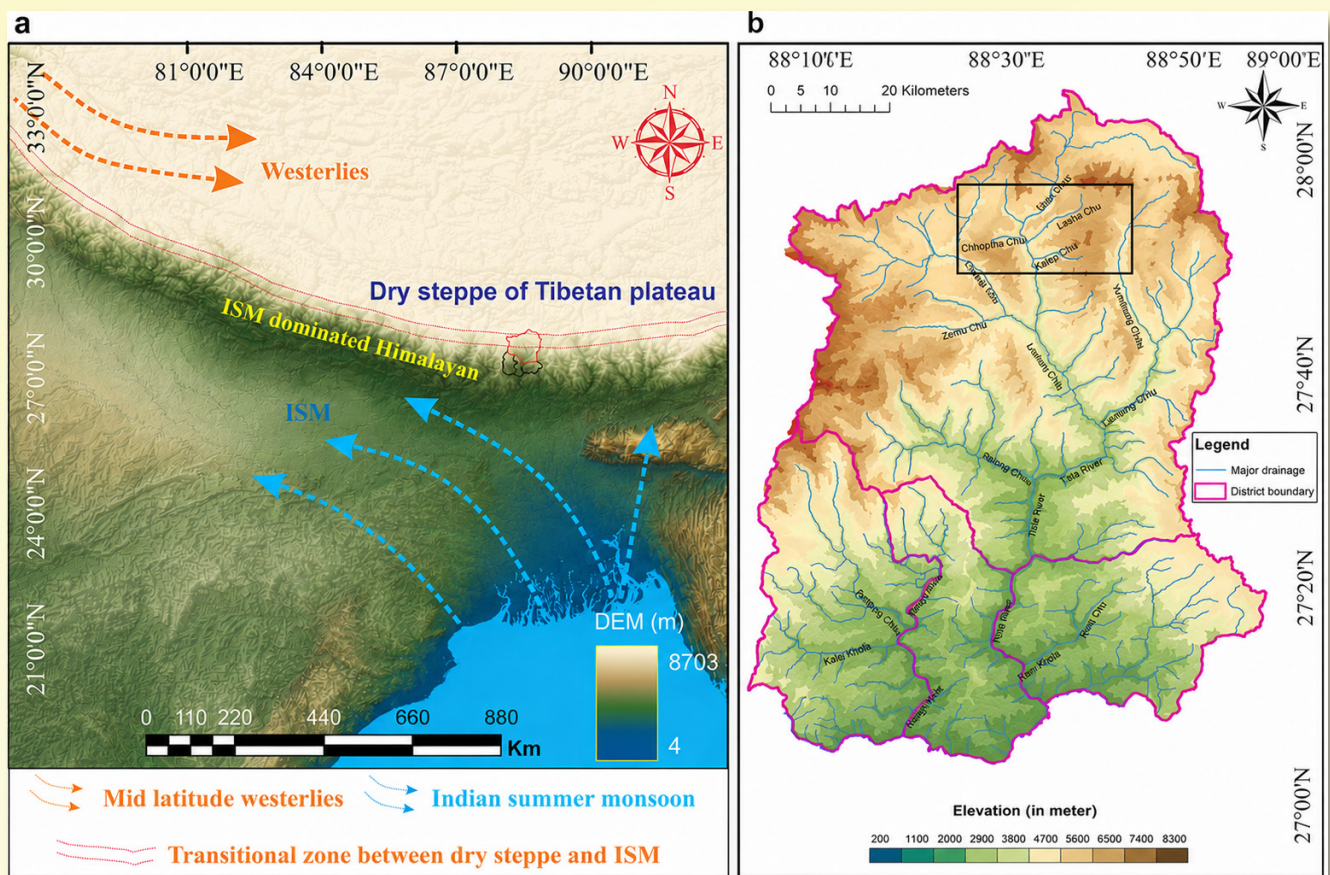


Figure 1. a) Shuttle Radar Topographic Mission (SRTM) map showing the regional setup of the area along with the trajectories of weather system, viz. the Indian summer monsoon and the mid-latitude westerlies shown by blue and orange dashed arrows. The polygon shows Sikkim state, and the two dotted lines demarcate the transitional zone between the dry steppe of Tibetan Plateau and the monsoon-dominated southern Himalaya; **b)** Shuttle Radar Topographic Mission (SRTM) Digital Elevation Map (DEM), district boundaries and major drainages of Sikkim state (after Dubey et al. 2019).

and Himalayan vegetation was gradually developing into communities different from those that existed during the preceding cold period.

The earliest part of the pollen sequence is marked by substantial fluctuations in pollen abundance and diversity. Such variability may reflect changing hydroclimatic conditions, but it may also partly result from the nature of the sedimentary archive itself. Coarser sediments, for example, may preserve pollen differently from finer, organic-rich deposits. This makes the earliest part of the record more difficult to interpret with confidence.

A clearer signal emerges during the Early Holocene. Between approximately 10,500 and 8,000 years ago, the pollen record indicates generally favourable hydroclimatic conditions accompanied by the rapid expansion of mixed broad-leaved forests. Pollen richness and alpha diversity also increased during this interval, suggesting that the vegetation community became both more extensive and more diverse. The Indian Summer Monsoon was likely an important factor in this transformation. Increased moisture availability would have created more favourable conditions for moisture-demanding woody vegetation

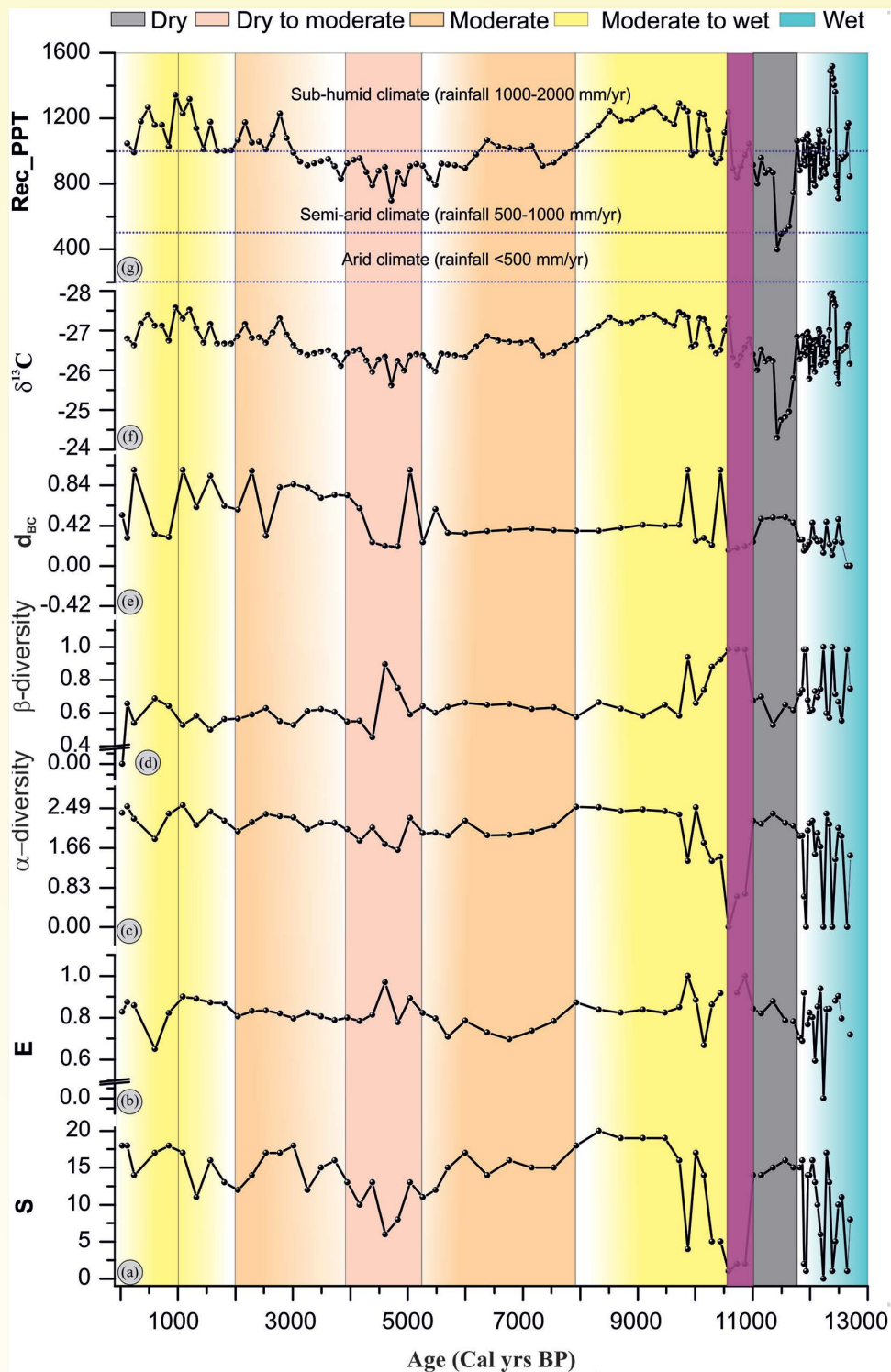


Figure 2. Showing the measured values of (a) plant richness (S), (b) evenness (E), (c) alpha diversity (α), (d) beta diversity (β), (e) dissimilarity index (d_{BC}), (f) Measured $\delta^{13}C$ value (‰; VBDB), (g) average reconstructed palaeoprecipitation values (mm) (Ali et al., 2018) of the sedimentary profile are shown against the depositional age (BP; 14C AMS). Different colour marks the zones with variation the rainfall from Dry (grey colour) to Wet/Intensified rainfall (blue colour). The purple colour marks the barren zone.

and allowed a wider range of forest elements to coexist. However, it would be too simplistic to describe this period merely as a “wetter Himalaya”. Vegetation responds to several interacting factors, including temperature, rainfall, seasonality, soil conditions, disturbance and competition. Pollen, therefore, records the ecological response to environmental change rather than functioning as a direct rainfall gauge.

When the forests became more diverse

Between about 8,000 and 5,500 years ago, the pollen record indicates continued expansion and diversification of woody vegetation. This period broadly overlaps with the Holocene Climate Optimum, a time of generally favourable climatic conditions in many parts of the world, although its timing and intensity varied from region to region.

One of the most interesting features of the Sikkim record is that this was not simply an increase in the abundance of a single dominant tree. Instead, the pollen assemblage suggests a broader diversification of woody vegetation. A diverse forest contains plants with different environmental tolerances and ecological strategies. Some are better adapted to moisture stress, while others are suited to particular temperature conditions, soils or levels of disturbance. In a mountainous landscape, such as the Himalaya, where environmental conditions can change considerably over relatively short distances and elevations, even modest climatic shifts can alter the availability of suitable habitats. Favourable hydroclimatic conditions may, therefore, have allowed a wider range of woody plants to establish and coexist, creating a richer and more complex vegetation community.

A period of ecological stress around 4,200 years ago

The vegetation story changed markedly after this favourable interval. Between about 5,500 and 4,000 years ago, the pollen record shows a decline in pollen abundance, richness and alpha diversity. This interval broadly encompasses the period associated with the

~4.2 ka cold event when there was a severe climate and aridity event that occurred, which has been recognised in palaeoclimate records from many parts of the world, although its expression was not uniform everywhere.

In the Sikkim record, the decline in vegetation indicators suggests that this period of climatic disturbance had a noticeable ecological impact in the Eastern Himalaya. One possible explanation is deterioration in hydroclimatic conditions. As moisture availability became less favourable, some forest elements may have contracted or become locally less successful, while plants better able to tolerate environmental stress may have gained a relative advantage. The overall result was a reduction in vegetation richness and diversity.

The pollen evidence should, however, be interpreted as part of a larger climatic picture rather than in isolation. A single proxy rarely captures the full complexity of past climate. When pollen changes are supported by independent sedimentological, isotopic, geochemical or biological evidence, confidence in the interpretation becomes much stronger. Vegetation is, therefore, one important witness among several that help reconstruct the environmental history of the Himalaya.

Forests recover, but not necessarily in the same form

The record becomes particularly interesting after 4.2 ka cold event (a period of ecological stress) as the pollen abundance and diversity began to recover between about 4,000 and 2,000 years ago, although the record remained variable. This interval is suggested as broadly warm and humid. This recovery provides an important insight into the resilience of Himalayan vegetation. Forest communities have repeatedly responded to environmental stress by changing their composition and distribution. They can contract under unfavourable conditions and expand again when the environment becomes more suitable.

Recovery, however, does not necessarily mean that the forest returns to exactly the same composition it had before the disturbance. An ecosystem can regain its diversity while the relative abundance and distribution

of individual plant groups change. Climate can alter which species are favoured, where they can survive and how different communities are assembled. Ecological recovery is, therefore, better understood as reorganisation and renewal rather than a simple return to the past.

The Last Thousand years

The youngest part of the sequence seems quite interesting. During approximately the last 1,000 years, pollen assemblage diversity shows an increasing trend. The study interprets this as evidence of broadly ameliorating climatic conditions and relates the pattern to the Medieval Climate Anomaly.

The Medieval Climate Anomaly is generally associated with relatively warm conditions in several parts of the world during medieval times, although its timing and intensity were not globally uniform. This regional variability is particularly important when interpreting Himalayan palaeoclimate records. Climate

does not affect every valley, elevation zone or mountain slope in exactly the same way. A climatic phase that produces warmer or wetter conditions in one region may have a different expression elsewhere.

The Sikkim record should, therefore, be viewed as a regional ecological archive, rather than a universal representation of Himalayan climate. Its significance becomes even greater when it is compared with other palaeoclimate records from the Himalaya and the wider monsoon region.

What vegetation diversity really tells us?

Perhaps the most important contribution of this study is its emphasis on vegetation diversity.

Pollen analysis is often used to answer a straightforward question: which plants were present in the past? But the diversity of the pollen assemblage can provide a broader perspective. It gives us information about the structure and complexity of the vegetation community.

The 13,000-year story at a glance

Period	Major environmental signal	Vegetation response
~13,000 years ago	Unstable transition into the Holocene	Strong fluctuations in pollen abundance and diversity; preservation may also have influenced the record
~10,500–8,000 years ago	Favourable hydroclimatic conditions	Expansion of mixed broad-leaved forests and increasing diversity
~8,000–5,500 years ago	Generally favourable conditions	Continued expansion and diversification of woody vegetation
~5,500–4,000 years ago	Climatic deterioration	Decline in pollen abundance, richness and alpha diversity
~4,000–2,000 years ago	Environmental improvement	Recovery of pollen abundance and diversity, although variable
Last ~1,000 years	Broad climatic amelioration	Increasing pollen diversity, broadly comparable with the Medieval Climate Anomaly

The Sikkim record suggests a recurring relationship between environmental conditions and vegetation diversity. During favourable hydroclimatic phases, forests expanded and became more diverse. During periods of environmental stress, pollen richness and diversity declined. When conditions improved again, vegetation diversity recovered.

This does not mean that vegetation diversity can be used as a simple measure of rainfall. Diversity represents an integrated ecological response to several environmental factors. It reflects the combined influence of climate, habitat availability, competition and other processes operating within the landscape.

In this sense, pollen diversity provides something more valuable than a simple climatic number: it shows how an ecosystem responded to changing environmental conditions.

Why this ancient record matters today

A sediment sequence that records vegetation history over 13,000 years at 4000 m a.s.l. (beyond the treeline) may initially seem far removed from the problems of the modern world. In reality, it provides an important long-term context for understanding current climate change. Today, Himalayan ecosystems are experiencing warming, changes in precipitation, land-use pressure, habitat fragmentation and other human influences. Instrumental observations provide valuable information about recent decades, but they cover only a very small fraction of the time during which Himalayan ecosystems have been changing.

Palaeoecological records provide a much longer baseline. They show that Himalayan vegetation has always responded dynamically to climate. Forests have expanded, contracted, diversified and reorganised in response to changing environmental conditions. This helps us distinguish natural long-term variability from more recent changes. At the same time, the modern situation is not simply a repetition of the past. Human activities can fragment habitats and restrict the ability of plants to migrate or reorganise naturally. Climate change is also occurring in combination with land-use and other environmental pressures.

The palaeo-record can, therefore, help us understand the range of responses that Himalayan ecosystems have displayed in the past and assess whether contemporary changes fall within, or extend beyond, the range of Holocene variability.

Beyond One Site: Seeing the Bigger Himalayan Picture

The 13,000-year record from Sikkim opens the door to a much broader set of questions.

Future studies involving high-resolution, multiproxy records from different elevations and valleys could help determine whether the approximately 4.2 ka climatic disturbance affected the Eastern Himalaya in a consistent manner. They could also investigate whether vegetation responded more strongly to changes in rainfall amount, rainfall seasonality, temperature or a combination of these factors.

Longer and better-resolved records could further reveal how rapidly Himalayan forests recovered after periods of climatic stress and whether fire or human activity strengthened or altered climate-driven vegetation changes.

These phases illustrate a landscape that repeatedly changed in response to environmental conditions rather than remaining fixed through time.

What the Himalaya remembers

A single pollen grain cannot tell us exactly how much rain fell thousands of years ago or what the temperature was on a particular day. But thousands of pollen grains preserved together, layer by layer, can reveal something much more meaningful— the long-term ecological history of a landscape.

The approximately 13,000-year pollen record from the higher Sikkim Himalaya reveals a vegetation system that was constantly responding to environmental change. Forests expanded when hydroclimatic conditions were favourable. Vegetation diversity increased during favourable intervals, declined during periods of climatic deterioration, and later recovered. The decline associated with the interval around the

4.2 ka climatic disturbance is particularly notable, while the increasing diversity during the youngest part of the record provides evidence of another period of environmental amelioration.

The broader lesson is not simply that the Himalaya has experienced wetter and drier phases. It is that climate and vegetation have always been closely connected. A change in climate can reorganise vegetation, while changes in vegetation can alter the way an ecosystem responds to its environment.

The sediments of the Himalaya have preserved the evidence of these ancient environmental changes for thousands of years. By learning to read that evidence carefully, palaeoecology allows us to look beyond the short instrumental record and understand how

Himalayan ecosystems behaved during a wide range of natural climatic conditions.

That long memory may be one of our most valuable tools for understanding how Himalayan forests could respond to the environmental changes unfolding today.

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About author



Dr Jyotsna Dubey is Birbal Sahni Research Associate (BSRA) at the BSIP, Lucknow. Her research focuses on reconstructing vegetation responses to past climate change in the Himalayan region. Her work particularly emphasizes the Himalayan region with the aim of understanding cryospheric changes during the recent geological past, as well as the relationships between climate and vegetation during recent and sub-recent periods.

When the Monsoon Roared: Assam's Ancient Lake Records a Medieval Climatic Anomaly

Swati Tripathi

CLIMATE change is not a new phenomenon. Long before weather stations, thermometers and satellites began recording the Earth's climate, nature itself was preserving evidence of environmental change. One of the most remarkable natural archives is lake sediments, where layer after layer of pollen grains, plant remains and microscopic organisms accumulate over centuries. These tiny remains can reveal how vegetation responded to changing temperature and rainfall and, in turn, allow scientists to reconstruct the climate of the past. A study from Chatla Lake in the Barak Valley of Assam, northeast India, provides one such window into the climate of the last millennium (Figure 1). The sedimentary record captures environmental changes between 580 and 1220 CE, spanning the period before, during and at the peak of the Medieval Warm Period (MWP), or Medieval Climate Anomaly (MCA). By combining fossil pollen and diatom evidence with quantitative estimates of temperature and precipitation, the study provides an important regional perspective on a climatic phenomenon that has also been recognized in palaeoclimate records from many parts of the world.

The Medieval Warm Period is one of the most discussed episodes of past climate variability. It is generally associated with a period of climatic anomaly during approximately 950-1250 CE, although its timing and intensity differed from region to region (Mann et al., 2009; Diaz et al., 2011). Modern research has moved away from the idea of a perfectly

synchronous, globally uniform warm period. Instead, global palaeoclimate syntheses show that the Medieval Climate Anomaly was expressed as a complex mosaic of regional warming, cooling, changes in precipitation and shifts in atmospheric and oceanic circulation. The global compilations of Lüning and colleagues are particularly important in this context. Their work brought together palaeoclimate evidence from numerous regions and demonstrated that Medieval climate variability had a strong geographical component (Lüning et al., 2018; 2019a; 2019b; Lüning et al., 2020). In some regions, warming was dominant, while other areas experienced cooling or changes primarily in hydroclimate. This global perspective makes records from monsoon regions especially valuable because they allow scientists to understand how a large-scale climate anomaly was translated into regional changes in rainfall and atmospheric circulation.

The Chatla Lake record adds an important piece to this global picture because it comes from the Indo-Burma region, an area strongly influenced by the South Asian Summer Monsoon. The study examined an 80-cm-long sediment core from Chatla Lake and reconstructed vegetation and climate through a sequence extending from 580 to 1220 CE. The fossil pollen assemblage was divided into four major phases corresponding to different ecological and climatic conditions (Figure 2). More importantly, the interpretation went beyond qualitative descriptions,

Fossil pollen, microscopic algae and quantitative climate reconstruction reveal how northeast India experienced a remarkably warm, wet and monsoon-intense phase during the Medieval Climate Anomaly

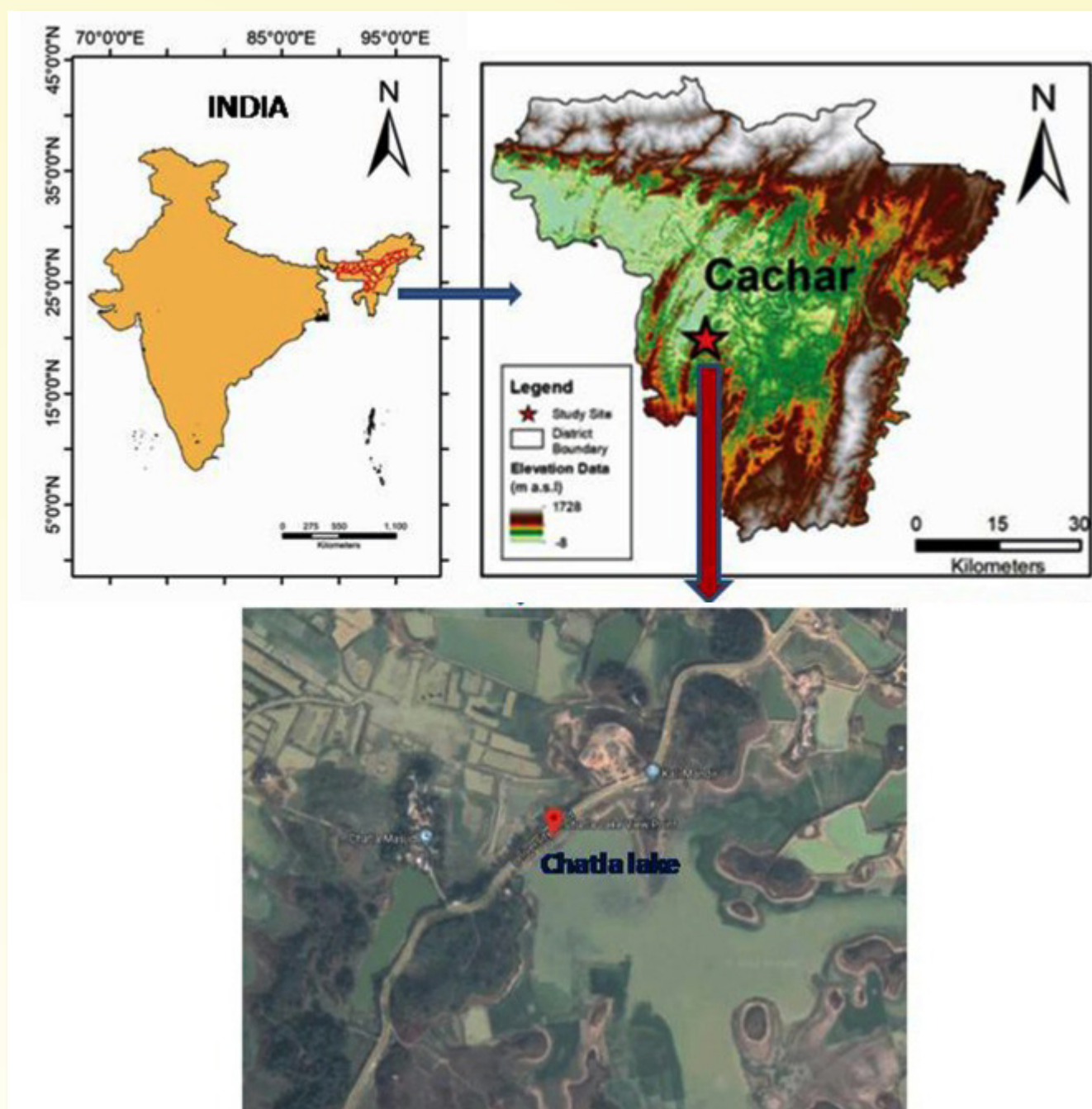


Figure 1. Location Map showing study site

such as “warm,” “cool,” “wet,” or “dry.” Instead, the Coexistence Approach was employed, using the climatic tolerances of the nearest living relatives of fossil pollen taxa to quantitatively estimate Mean Annual Temperature (MAT) and Mean Annual Precipitation (MAP) (Mosbrugger and Utescher, 1997). By converting fossil pollen evidence into numerical

climatic estimates, this approach provides a more robust basis for reconstructing past environmental conditions and enables meaningful comparisons with palaeoclimate records from other regions of the world.

The first phase, between 580 and 760 CE, provides a climatic baseline before the strongest Medieval Climate Anomaly signal developed. During

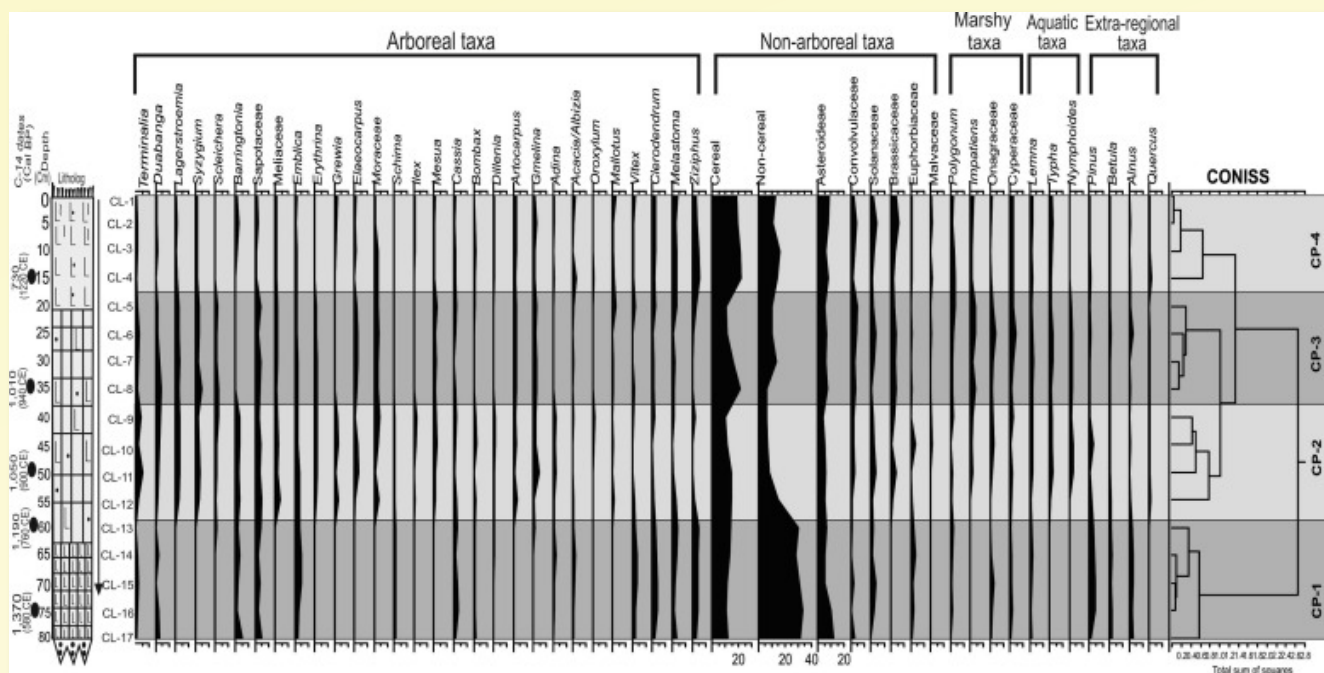


Figure 2. Pollen frequency diagram from Chatla Lake, Cachar District, Assam.

this interval, the vegetation around Chatla Lake was relatively open, with considerable representation of grasses and non-cereal pollen, while tropical mixed deciduous trees occurred in lower frequencies. *Riparian* tree taxa, such as *Barringtonia*, *Duabanga* and *Sapotaceae* were present, but the overall pollen assemblage suggests less extensive forest development than in the succeeding centuries. The relatively low abundance of arboreal pollen, together with scanty diatom occurrence, points towards a warm but comparatively less humid climate and a weaker Southwest Monsoon. Thus, the Barak Valley was already experiencing climatic variability before the onset of the more pronounced Medieval warm-humid phase. A major transformation began around 760 CE. Between 760 and 940 CE, the vegetation record shows the development of a much more substantial tropical mixed deciduous forest. Pollen from *Duabanga*, *Lagerstroemia*, *Syzygium*, *Terminalia* and *Barringtonia*, together with semi-evergreen taxa, became increasingly abundant. Moisture-loving plants, such as *Impatiens* and *Convolvulaceae* also became more prominent. These changes indicate increasingly favourable conditions for forest growth and suggest strengthening monsoonal activity. The quantitative

reconstruction reveals a broad climatic range during this phase, with MAT estimated at approximately 18–27 °C and MAP at approximately 538–1875 mm. Rather than representing a simple and uninterrupted warming trend, this broad range indicates substantial seasonality and hydroclimatic variability. The study also discusses possible links with ENSO-related variability, illustrating that the Medieval climate was dynamic rather than uniformly stable.

The most remarkable part of the record appears between 940 and 1220 CE, corresponding to the peak Medieval Warm Period signal at Chatla Lake (Figure 3). During this interval, tropical mixed deciduous forest became well established under conditions interpreted as strongly influenced by the Southwest Monsoon. The presence of moisture-loving, marshy and aquatic plants including *Impatiens*, *Lemna*, *Myriophyllum*, *Typha* and *Potamogeton* indicates that water availability was high and that the lake remained a favourable aquatic environment. The quantitative palaeoclimate reconstruction provides particularly striking values: the maximum Mean Annual Temperature reached approximately 31 °C, while Mean Annual Precipitation reached approximately 2250 mm. These represent the highest maximum MAT and MAP values

Highly humid climatic zones (strong monsoonal activity) corresponding to MWP	Identified marker pollen taxa	Marker diatom taxa
1190–1010 cal. BP (760–940 CE)	<i>Terminalia</i> , <i>Duabanga</i> , Sapotaceae, <i>Syzygium</i> , <i>Schima</i> , <i>Impatiens</i> , <i>Polygonum</i> , Onagraceae, Cyperaceae and <i>Nymphoides</i> .	<i>Aulacoseira</i> , <i>Cyclotella</i> , <i>Amphora</i> , <i>Pinnularia</i> and <i>Cymbella</i>
1010–730 cal. BP (940–1220 CE)	<i>Terminalia</i> , Meliaceae, Moraceae, <i>Gmelina</i> , <i>Impatiens</i> , <i>Polygonum</i> , <i>Lemna</i> and <i>Typha</i> .	<i>Aulacoseira</i> , <i>Cyclotella</i> , <i>Amphora</i> , <i>Pinnularia</i> , <i>Cymbella</i> , <i>Stauro-neis</i> and <i>Surirella</i> .

Table 1. Identified marker pollen and diatom taxa for high monsoonal activity during MWP in the Barak valley, Assam.

reconstructed from the studied sequence. These numbers are important because they give a quantitative dimension to the term “Medieval Climatic Anomaly.” The evidence from Chatla Lake suggests that the peak MCA in northeast India was not simply characterized by higher temperature. It involved the combined influence of warm conditions, substantial precipitation and enhanced monsoonal activity. The development of dense tropical forest indicates favourable moisture conditions on land, while the abundance of aquatic and marshy plants points towards sustained water availability. In this sense, the Chatla record provides a distinctive monsoon fingerprint of the Medieval Climate Anomaly. It shows how a climatic anomaly recognized in global palaeoclimate syntheses could be expressed in a monsoon-dominated environment through simultaneous changes in temperature, precipitation, seasonality and vegetation.

The pollen evidence is further strengthened by the diatom record. Diatoms are microscopic, single-celled algae found mainly in aquatic environments. They have silica (SiO₂) cell walls, called frustules, which give them their characteristic shapes. Because diatoms are sensitive to changes in water availability, nutrient levels, mixing, temperature, and other ecological conditions, they are widely used as bioindicators of aquatic environmental conditions. Their abundance and composition can, therefore, provide an independent indication of changes occurring within a lake. During the 940–1220 CE interval, the Chatla Lake sediments

show increased diatom abundance, including a rise in planktonic forms, such as *Aulacoseira*. The increased representation of *Aulacoseira* during this interval supports the pollen-based interpretation of enhanced precipitation and stronger monsoonal conditions. The agreement between the terrestrial pollen record and the aquatic diatom record is particularly valuable because the two proxies respond to different aspects of the environment. In simple terms, the vegetation around the lake and the microscopic organisms living within it were recording the same broad climatic change.

Lüning et al. (2018, 2019 a, b, 2020) demonstrated that the Medieval Climate Anomaly was not a uniform global warming event in which every region experienced identical conditions at exactly the same time. Instead, the MCA was characterized by substantial spatial variability, with different regions showing different combinations of temperature and hydroclimatic responses. Their compilations from Africa, Antarctica, Mediterranean region, Australia, New Zealand and West Papua illustrate this complexity particularly well. Some regions show evidence of warming, while others experienced cooling or significant changes in moisture availability. The Chatla Lake record fits naturally within this broader framework: it represents the regional expression of the Medieval Climate Anomaly in the monsoon-dominated Indo-Burma region, where the most conspicuous response was enhanced warmth and humidity accompanied by stronger southwest monsoon activity (Tripathi et al., 2021).

This comparison also highlights the importance of geographical coverage in global palaeoclimate reconstruction. While Europe and several other regions have relatively extensive palaeoclimate datasets, many parts of the tropics and monsoon Asia remain comparatively underrepresented, particularly for the last millennium. A quantitative record from the Barak Valley, therefore, contributes more than another local climate history. It helps fill a geographical gap in the global MCA database and provides information from a region where climate is strongly controlled by the seasonal monsoon. The record demonstrates that the global MCA cannot be fully understood without examining the behaviour of regional climate systems, such as the Indian Summer Monsoon.

The Chatla Lake evidence also reminds us that temperature and rainfall do not necessarily change in the same way everywhere. In some regions, a Medieval Climate Anomaly may be expressed primarily through warming; elsewhere, changes in drought or precipitation may dominate. In the Barak Valley, the strongest signal is a combination of warmth and

enhanced moisture. The reconstructed maximum values of approximately 31 °C MAT and 2250 mm MAP during 940–1220 CE, together with forest expansion and increased aquatic indicators, point towards a period of particularly favourable moisture conditions. This makes the record especially relevant for understanding how the South Asian Monsoon responded during the Medieval Climate Anomaly. The story changes again after 1220 CE. The post-MCA phase records a decline in arboreal pollen and an increase in cereal pollen and secondary shrubs, such as *Melastoma*, *Clerodendrum* and *Justicia adhatoda* (Figure 4). The vegetation evidence indicates increasing landscape disturbance and human activity. At the same time, the reconstructed climatic range declined to approximately 16–28 °C MAT and 380–1700 mm MAP, indicating relatively less warm and humid conditions compared with the MWP peak. The rise in cereal pollen suggests expanding agricultural activity, while changes in the diatom assemblage provide additional evidence of ecological disturbance. The landscape was, therefore, being shaped by two

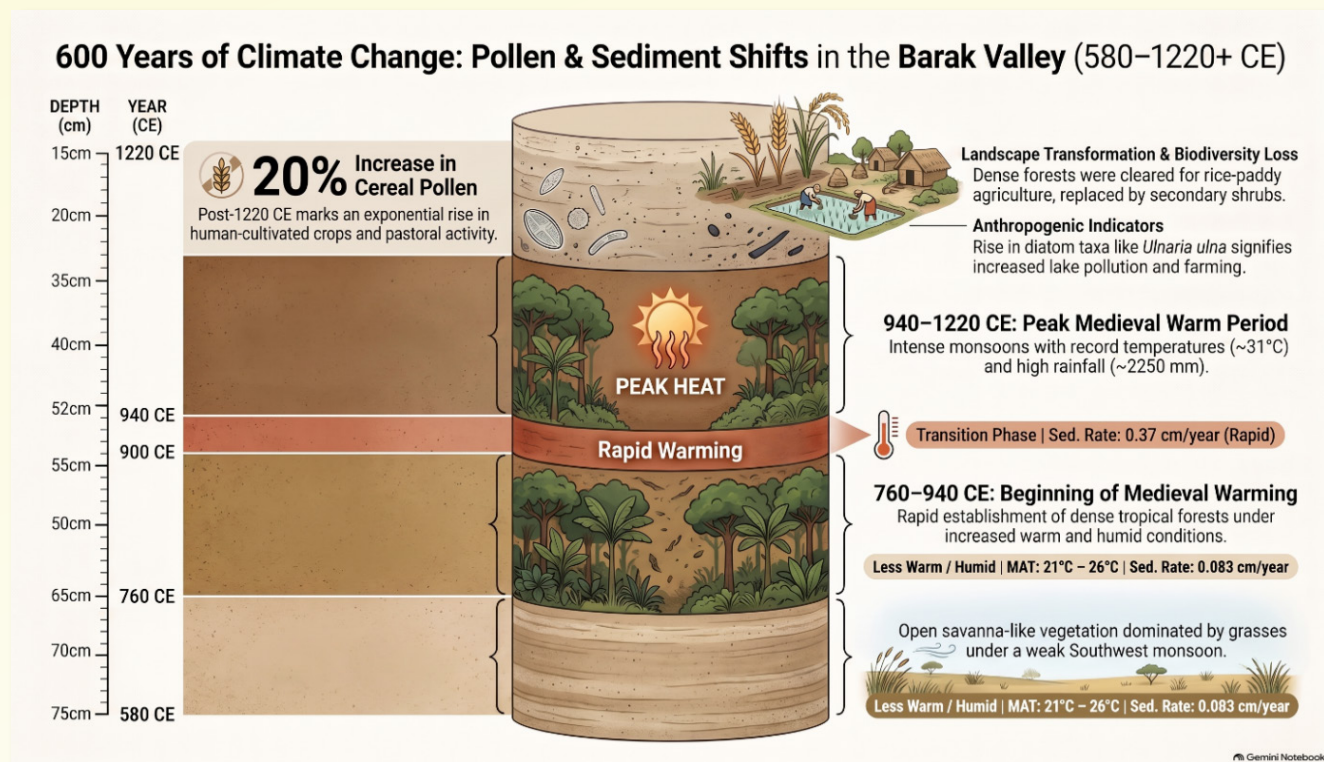


Figure 3. 600 years of Climate change: Pollen and sediment shifts in the Barak Valley (580-1220 CE).

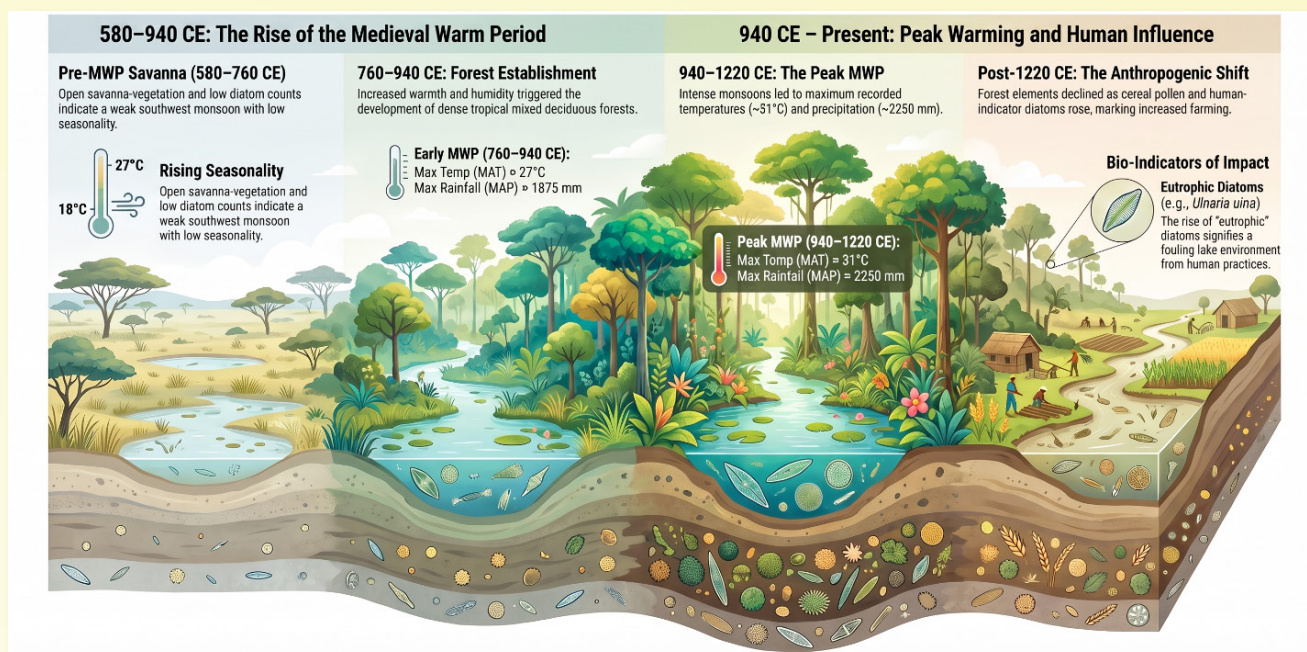


Figure 4. A journey through time: Ecological change in the Barak Valley (580 CE-Present).

increasingly important forces, climate variability and human activity.

This transition is particularly interesting because it demonstrates how palaeoecological records can capture the gradual shift from a predominantly climate-driven landscape to one increasingly modified by people. During the MWP peak, the expansion of forest appears closely associated with favourable climatic conditions. After 1220 CE, however, declining arboreal pollen occurs alongside increasing cereal and secondary vegetation, suggesting that human land use was becoming an increasingly important factor. The record, therefore, provides a long-term perspective on the interaction between climate and human activity, an issue that remains central to environmental change today.

The quantitative nature of the study is one of its greatest strengths. Pollen assemblages provide information about vegetation (Figure 5), but by applying the Coexistence Approach, those biological observations can be translated into estimates of past climatic conditions. The method uses the known climatic tolerances of the nearest living relatives of fossil taxa to identify the climatic range within which

the fossil assemblage could have existed. This allows palaeoclimatologists to move from a statement, such as “the forest indicates a warm and humid environment” to a more informative assessment of how warm and how wet that environment may have been.

Such numerical reconstructions are essential for building regional and global palaeoclimate maps. A single record can tell us about one place, but when comparable records from different regions are brought together, scientists can investigate whether climatic anomalies were synchronous, how their intensity varied geographically and what mechanisms may have driven them. The Chatla Lake study provides an important contribution to this broader effort by adding a quantitative, multi-proxy record from northeast India.

The broader significance of the study, therefore, extends well beyond the Barak Valley. The record demonstrates that the climate of northeast India underwent substantial changes during the last millennium and that the Indian Summer Monsoon was capable of considerable variability during the Medieval Climate Anomaly. It also shows that regional climate responses can be reconstructed by combining

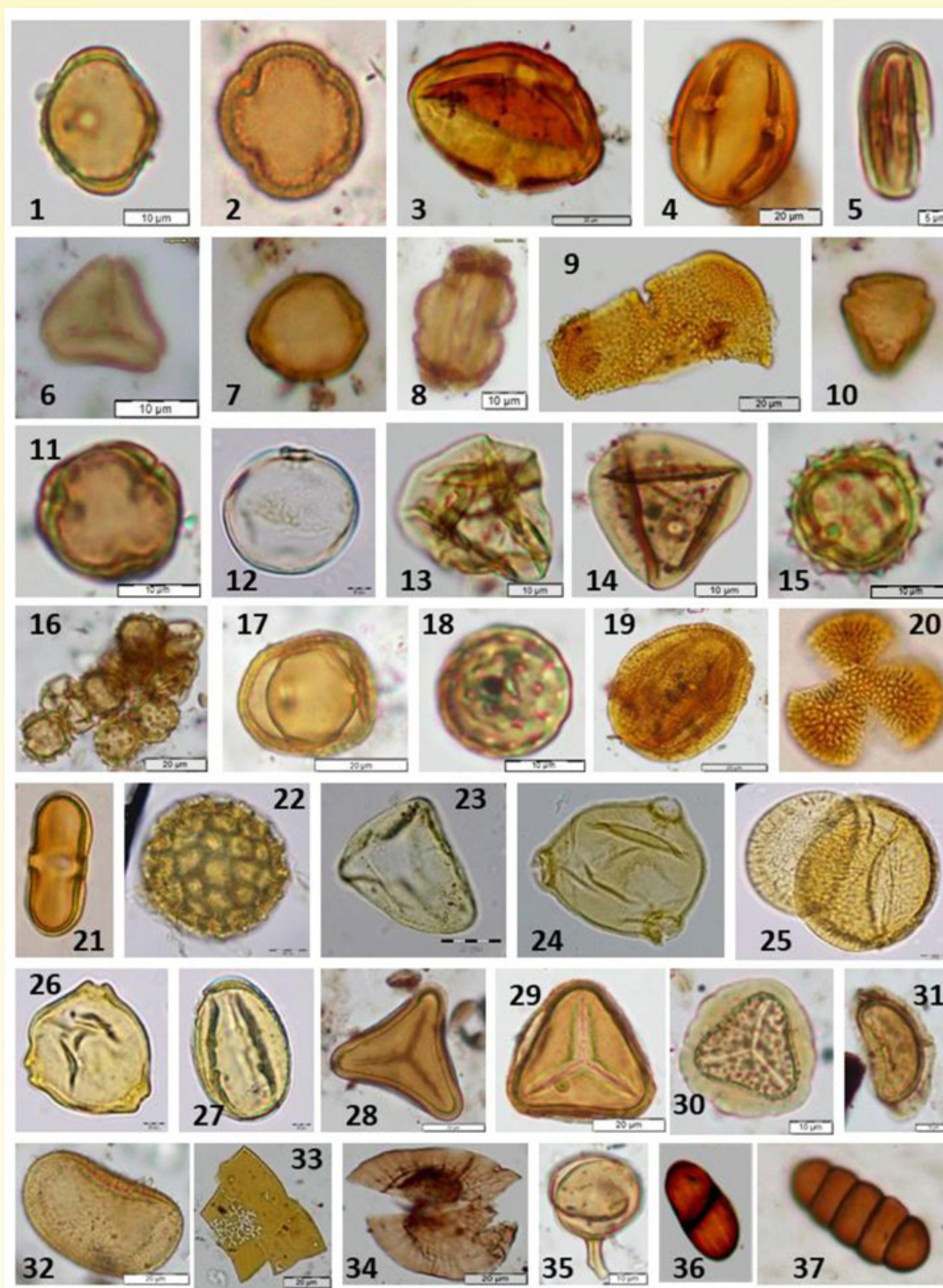


Figure 5. Pollen and non-pollen palynomorphs retrieved from the sediments of Chatla Lake, Assam. 1. *Duabanga*, 2. *Emblica*, 3 & 4. Sapotaceae, 5. *Elaeocarpus*, 6. *Syzygium*, 7. Moraceae, 8. *Barringtonia*, 9. *Bombax ceiba*, 10. *Schleichera*, 11. Solanaceae, 12. Non-cereal, 13 & 14. Cereal, 15. Asteroideae, 16. Clumps of Asteroideae, 17. *Xanthium*, 18. Amaranthaceae, 19. Convolvulaceae, 20. *Brassica*, 21. *Coriandrum*, 22. *Polygonum*, 23. Cyperaceae, 24. *Ludwigia*, 25. *Pinus*, 26. *Betula*, 27. *Quercus*, 28–30. Trilete spores, 31 & 32. Monolete spores, 33. Organic matter showing wedge shaped fungal infection, 34. Microthyriaceous fruiting body, 35. *Glomus*, 36. Ascospore of *Cookeina*, 37. *Meliola* type.

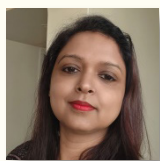
different natural archives. Pollen tells us about the surrounding vegetation, diatoms record changes in the lake environment, and quantitative palaeoclimate methods provide numerical estimates of temperature and rainfall. When these independent lines of evidence converge, they create a much stronger picture of past climate.

The Chatla Lake record ultimately changes the way we might imagine the Medieval Warm Period. It was not simply a period when “the world became warmer.” Rather, it was a time of complex climate variability, expressed differently across different regions. In northeast India, one of its clearest signatures appears to have been a combination of high temperature, abundant rainfall, strong seasonality and an intensified southwest monsoon. The interval between 940 and 1220 CE, with reconstructed maximum MAT of about 31 °C and MAP of about 2250 mm, represents the strongest warm-humid phase identified in the studied sequence. Nearly a thousand years later, the evidence remains remarkably clear. The forests that once surrounded Chatla Lake are gone or transformed, the people and landscapes of the Barak Valley have changed, and the climate continues to evolve. Yet microscopic pollen grains and diatoms preserved in layers of ancient sediment still carry the imprint of a time when the monsoon behaved differently. From the global climate records compiled by Lüning and colleagues to a tiny lake in Assam, the evidence points to the same fundamental lesson: Earth’s climate has always been dynamic, regional and interconnected. And sometimes, the most powerful stories of global climate change are written not in ice or instruments, but in a grain of pollen preserved in ancient mud.

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About author



Dr Swati Tripathi is Senior Scientist in the Quaternary Palaeoclimate Laboratory, BSIP, Lucknow. Her work focuses on reconstructing Quaternary vegetation, climate, and depositional environments through a range of biotic and abiotic proxy analyses.

The Magnetic Memory of a Lake: How Tiny Minerals Reveal the History of the Indian Monsoon

Nazakat Ali and Biswajeet Thakur

At first, the connection may seem surprising. What could magnetism possibly have to do with rainfall that occurred thousands of years ago? The answer lies quietly beneath the waters of Bakhira Lake, a large natural wetland in the Central Ganga Plain of Uttar Pradesh, India. Year after year, sediments have accumulated on its floor. These sediments contain material eroded from the surrounding landscape and transported into the lake by rivers, runoff and other processes. Among the clay, silt and sand are tiny magnetic minerals that can preserve clues about the environmental conditions under which the sediments formed. By studying these minerals, scientists can reconstruct how the landscape and monsoon changed through time. A recent environmental-magnetic study of Bakhira Lake has produced a continuous record extending back approximately 25,000 years, providing a long-term view of Indian Summer Monsoon variability from the Last Glacial Maximum to the Late Holocene.

Bakhira Lake lies in the Sant Kabir Nagar district of eastern Uttar Pradesh, within the low-lying landscape of the Central Ganga Plain (Figure 1). The lake is situated west of the Rapti River and is connected to the surrounding fluvial system. Its shallow setting, together with the network of rivers, palaeochannels, floodplains and marshy areas around

it, makes the region particularly sensitive to changes in rainfall and runoff. This sensitivity is useful to palaeoclimatologists.

When monsoon rainfall increases, runoff can become stronger and more sediment may be transported from the surrounding catchment towards the lake. At the same time, warmer and wetter conditions can enhance chemical weathering and soil formation. During drier conditions, these processes may weaken and the character of the sediment entering the lake can change. The sediment, therefore, provides a kind of environmental diary; but it is written in minerals rather than words. To read this diary, researchers recovered a 4.06-m-long sediment sequence from the lake. More than 200 samples were analysed at closely spaced intervals. Seven AMS radiocarbon dates were used to establish the chronology, and the resulting age–depth model indicates that the sequence extends back approximately 25,300 years.

Where does the magnetism come from?

Lake sediment is not inherently magnetic. Its magnetic properties come mainly from minerals containing iron. Two important minerals identified in the Bakhira sediments are magnetite and hematite. They respond differently to a magnetic field. Magnetite

How can a handful of magnetic minerals preserved in lake mud reveal the history of the Indian monsoon

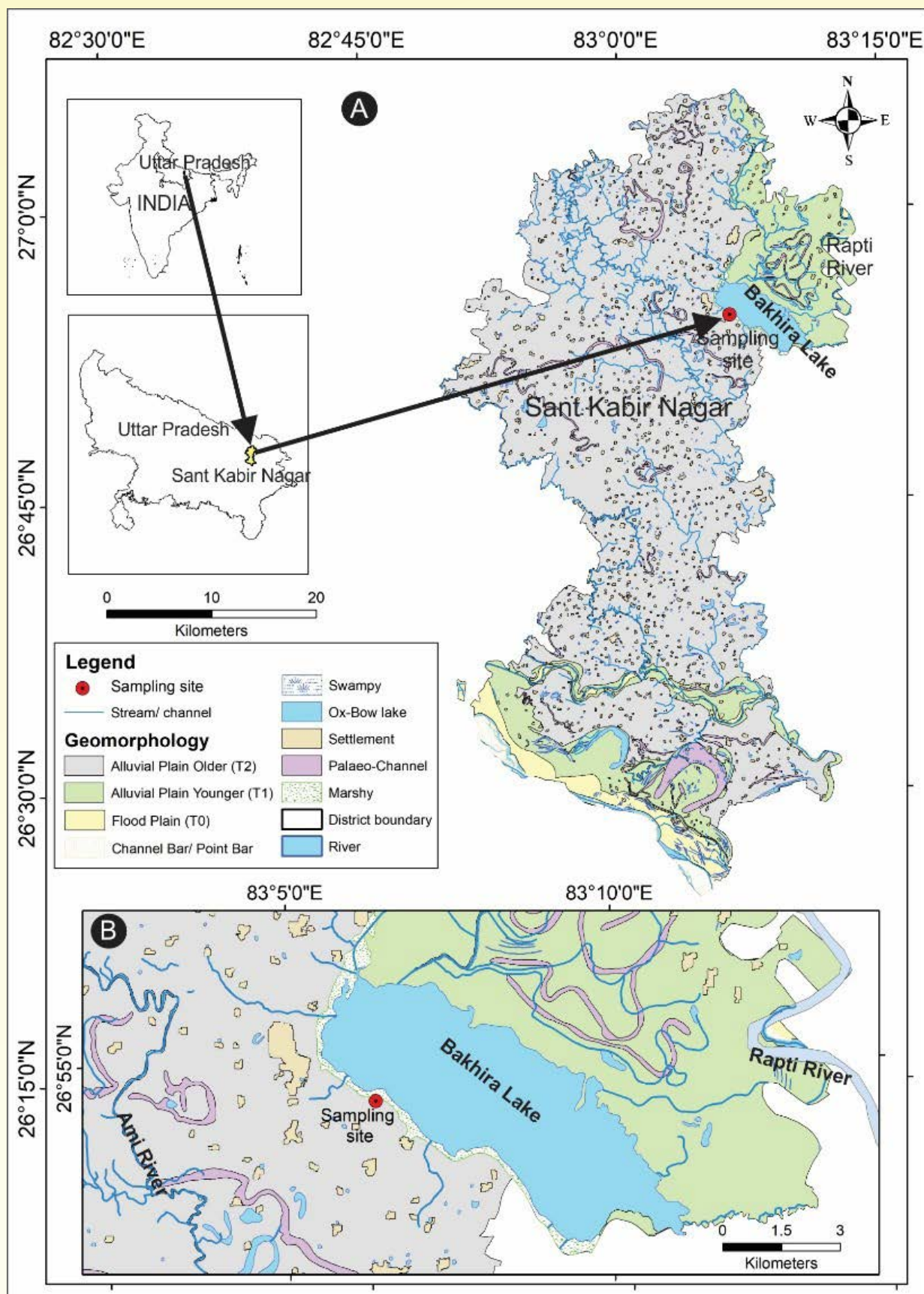
is relatively easy to magnetize, whereas hematite has much higher coercivity and behaves differently under applied magnetic fields. This difference gives scientists a useful opportunity. By measuring the magnetic properties of sediments, they can estimate not only how much magnetic material is present, but also which types of magnetic minerals dominate and whether their grain sizes have changed. Several measurements were, therefore, carried out on the Bakhira samples, including magnetic susceptibility, frequency-dependent susceptibility, anhysteretic remanent magnetization and saturation isothermal remanent magnetization. Additional parameters were used to investigate magnetic mineralogy and grain size. For a non-specialist reader, these measurements can be thought of as different ways of asking the same basic question.

Before using magnetic minerals as indicators of past climate, there is an important scientific problem to solve. Magnetic minerals can have several origins. They may be transported into a lake from the surrounding rocks and soils, produced during soil formation, or modified after burial. If the magnetic signal is changed significantly after deposition, it may no longer faithfully represent the environmental conditions at the time the sediment accumulated. The Bakhira study, therefore, examined the possible sources of the magnetic minerals. The results indicate that the magnetic assemblage is dominated by detrital magnetite and hematite, derived primarily from the catchment. The study found no significant evidence for bacterial magnetite or greigite, and there was no indication that substantial post-depositional alteration had erased the original magnetic signal. This assumption is important because it gives greater confidence that variations in the magnetic record reflect changes in catchment conditions rather than simply changes occurring inside the sediment after deposition.

The subsequent stage is to understand why climate should influence magnetic minerals. Under warm and humid conditions, chemical weathering and soil formation can become more intense. These processes may favour the formation of very fine magnetic particles in soils. Some of these particles

can eventually reach the lake through erosion and runoff. One particularly useful parameter is frequency-dependent magnetic susceptibility, or $\chi_{fd}\%$. Higher values generally indicate a greater contribution from very fine, superparamagnetic particles. In the Bakhira sequence, enhanced $\chi_{fd}\%$ values occur during intervals interpreted as warmer and wetter, when pedogenic activity was stronger. Other parameters provide complementary information (Figure 2). The S-ratio, for example, helps distinguish relatively low-coercivity minerals, such as magnetite from high-coercivity minerals, such as hematite. Magnetic grain-size indicators help determine whether the magnetic assemblage contains relatively fine or coarse particles. Importantly, the interpretation does not depend on a single magnetic measurement. The researchers considered several magnetic parameters together and compared them with grain-size, clay-mineralogical and geochemical evidence from the same sediment sequence. That combination is one of the strengths of the reconstruction.

Once the magnetic signal was established as reliable, it could be used to investigate changes in hydroclimate. The oldest part of the record, approximately 25.3–18.1 thousand years ago, contains relatively low magnetic concentrations and a greater contribution from high-coercivity minerals. When considered together with the other sedimentary evidence, these characteristics indicate relatively cold and dry conditions, weaker runoff and enhanced physical weathering. This interval broadly encompasses the Last Glacial Maximum (LGM). The story changes after the glacial period. Between approximately 18.1 and 16.8 thousand years ago, magnetic evidence indicates stronger catchment activity and an increase in monsoon strength. This improvement was followed by another weakening between approximately 16.8 and 15.3 thousand years ago, corresponding broadly to Heinrich Stadial 1. The monsoon strengthened again during the Bølling–Allerød, approximately 15.3–12.8 thousand years ago. But this relatively favourable interval was followed by another weakening during the Younger Dryas, between approximately 12.8 and 11.1 thousand years ago. These alternating



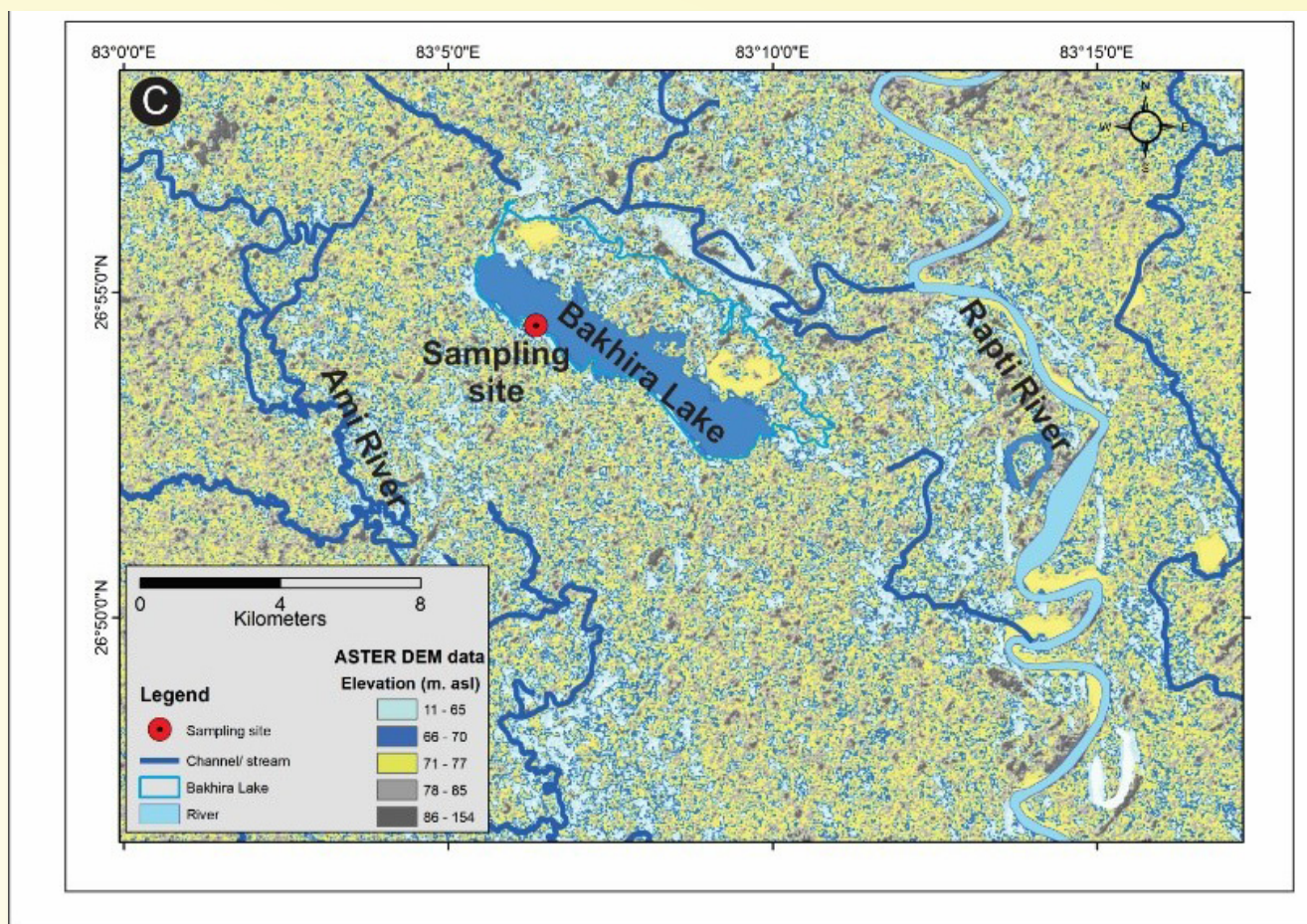


Figure 1. Location and geomorphological setting of Bakhira Lake, showing the sampling site, surrounding drainage network, major geomorphic units, and regional elevation.

phases demonstrate something fundamental about the monsoon: its history is not a simple story of gradual change. The system has responded repeatedly to climatic disturbances occurring at different timescales.

The Holocene provides another important part of the story. Between approximately 9.2 and 4 thousand years ago, the Bakhira sediments contain stronger evidence for fine magnetic grain formation and enhanced pedogenic activity. These characteristics, together with the other proxy evidence, indicate warmer and wetter conditions and a stronger monsoon. This interval broadly corresponds to the Holocene Climatic Optimum (HCO). The monsoon subsequently weakened. Between about 4 and 2 thousand years ago, the magnetic record indicates reduced catchment

activity and weaker monsoon conditions. This interval broadly coincides with the 4.2 ka aridity event, which has been recognised in several palaeoclimate records from South Asia. After approximately 2 thousand years ago, the Bakhira record indicates another phase of strengthened monsoon activity. Thus, the lake preserves not only long-term trends but also repeated departures from those trends. Perhaps the most intriguing aspect of the Bakhira record is that its story does not stop at the lake. The reconstructed monsoon variability broadly corresponds with evidence from other terrestrial and marine records, as well as speleothem and Greenland ice-core records. These comparisons suggest that long-term monsoon changes were strongly related to variations in Northern

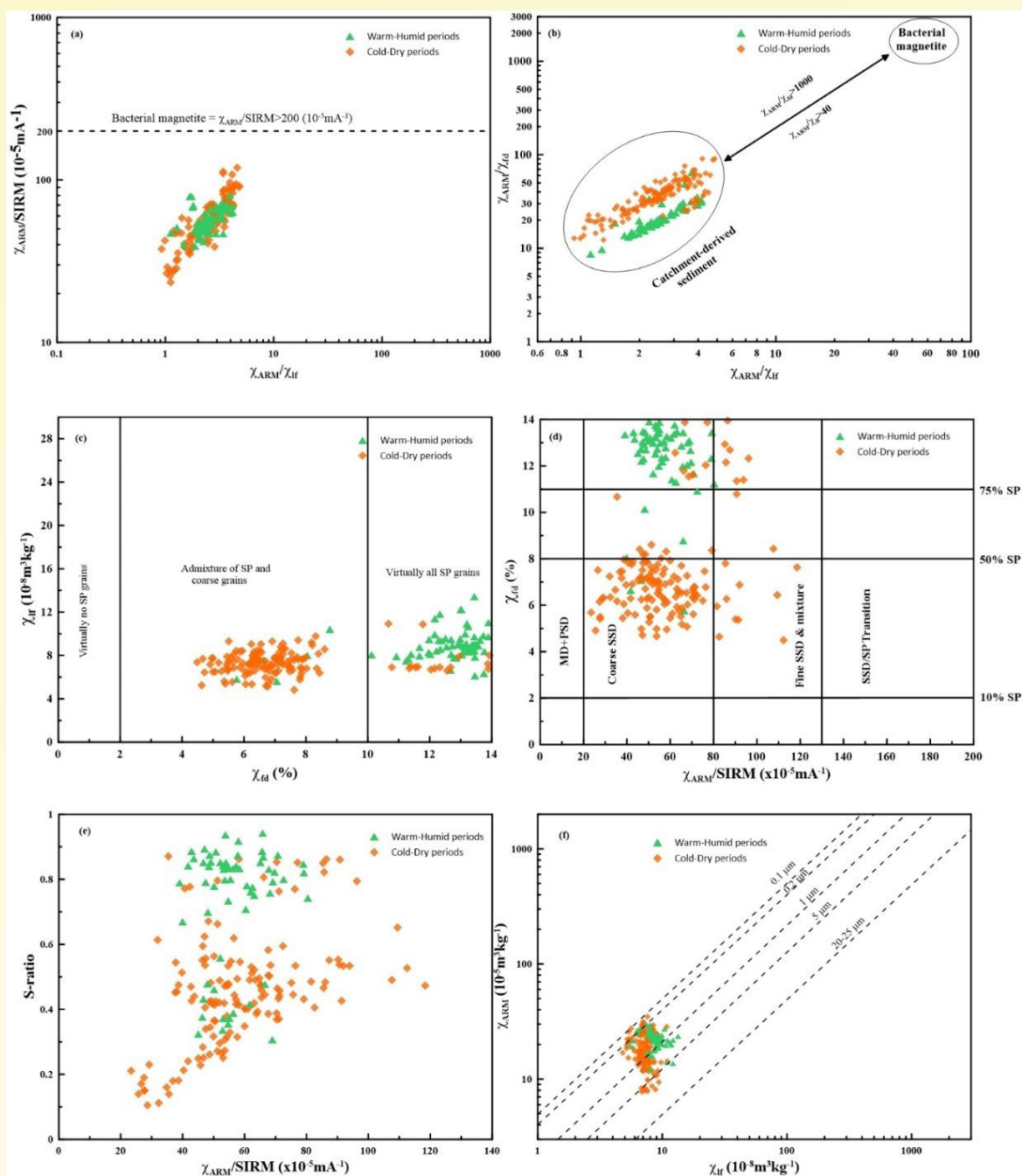


Figure 2. Biplots of magnetic parameters and inter-parametric ratios showing variations in magnetic grain size, mineralogy and the catchment-derived magnetic signal in Bakhira Lake sediments.

Hemisphere summer insolation. At the same time, abrupt events, such as Heinrich Stadial 1 and the Younger Dryas point towards the influence of large-scale reorganisations of the climate system (Figure 3). One mechanism involves changes in the Atlantic

Meridional Overturning Circulation (AMOC). Major disturbances in the North Atlantic can alter the distribution of heat between the northern and southern hemispheres. These changes can influence the position of the Intertropical Convergence Zone

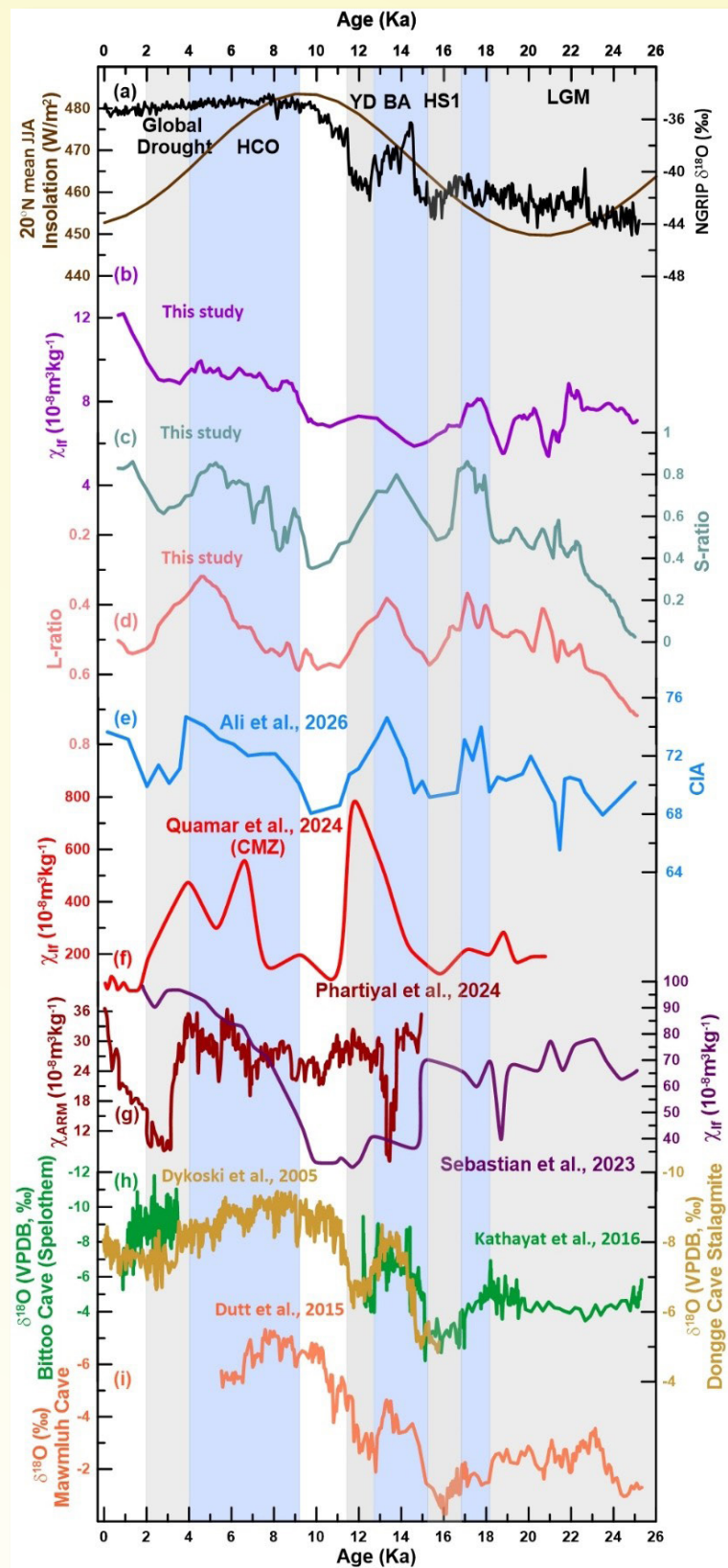


Figure 3. Comparison of the Bakhira Lake magnetic record with regional monsoon archives, Northern Hemisphere summer insolation and high-latitude climate records over the last ~25 ka.

(ITCZ), an important belt of tropical convection and rainfall, and consequently affect monsoon circulation over South Asia. In this sense, the sediments of Bakhira Lake provide an example of how a local geological archive can preserve evidence of a much larger climate system.

The Indian Summer Monsoon is central to life across South Asia. Agriculture, river flow, groundwater recharge and wetland ecosystems all depend, directly or indirectly, on its seasonal behaviour. Yet instrumental observations cover only a relatively short part of the Earth's climatic history. They cannot show us the full range of natural monsoon variability. That is where palaeoclimate records become valuable. The Bakhira Lake record extends the perspective from decades and centuries to tens of thousands of years. It shows that the monsoon has naturally undergone substantial fluctuations, including periods of strengthening and weakening associated with both gradual orbital forcing and abrupt climate events. This does not mean that the past provides a simple forecast of the future. The modern climate system is also being affected by

human-driven changes that have no exact counterpart in the geological record.

It tells us how sensitive the monsoon has been to changes in the wider climate system and reminds us that rainfall over the Indian subcontinent is connected to processes operating across the Earth. And that is perhaps the most remarkable lesson from Bakhira Lake. What appears to be ordinary mud at the bottom of a quiet wetland is, in fact, an archive of climate history. Within it are tiny magnetic minerals almost invisible to the eye, but capable of preserving evidence of how the landscape, rainfall and monsoon changed through time.

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About authors



Mr Nazakat Ali is pursuing Ph.D. from BSIP, Lucknow. His research focuses on Indian Summer Monsoon variability using multi proxy approach, including grain-size studies, clay mineralogy, geochemistry, palynofacies analysis, and environmental magnetism.



Dr Biswajeet Thakur is currently serving as Scientist 'F' at the BSIP, Lucknow. His research focuses on multi-proxy approaches to investigate past climate variability across diverse geographical settings, particularly the western and eastern coastal margins of India.

Beyond Warm and Cold: What Earth's Climate History can tell us

Debarati Nag

"You are studying the same thing again—warm and cold climates, just at older (Tertiary) time period."

It was a simple question... but it stayed with me.

As a palaeoclimate scientist, I spend much of my time trying to understand climates that disappeared long before humans began recording temperature, rainfall or atmospheric composition. We study sediments, rocks, fossils, pollen, minerals, isotopes and many other clues preserved in the Earth. From these fragments, we reconstruct worlds that no human ever witnessed.

But the question is fair.

The Earth has always changed. There have been periods when glaciers covered vast areas of the planet, periods when polar regions were much warmer than today, episodes of rapid warming and intervals when sea level stood far above its present position. If climate change is a natural part of Earth's history, why do scientists keep studying it? Haven't we already collected enough data? The answer begins with a simple realisation: We are not studying the past merely to find out whether the Earth was warm or cold. We are studying the past to understand what caused the change, how quickly the Earth responded, which parts of the climate system responded first and what feedbacks amplified or reduced the original disturbance.

A planet that has never stood still

Earth is about 4.6 billion years old. During this enormous span of time, its climate has moved through states that are difficult even to imagine. Consider one of the most extraordinary examples: the **'Snowball Earth' episodes of the Neoproterozoic**, roughly 720–635 million years ago. Geological evidences indicates that glaciers existed at very low, possibly near-equatorial latitudes. In the classical Snowball Earth interpretation, ice extended across much of the planet, potentially covering even tropical oceans. Imagine looking toward the equator and instead of tropical forests and warm oceans, seeing snow and ice. It sounds almost impossible. Yet rocks deposited hundreds of millions of years ago preserve evidence of these extraordinary conditions. Earth has experienced the opposite extreme as well. During the **Cretaceous**, particularly the mid-Cretaceous (120-90 million years ago) greenhouse interval, the planet was substantially warmer than today. Permanent polar ice sheets were absent, polar regions were much warmer and global sea level may have been roughly **100-200 metres higher than today**. A sea level more than a hundred metres higher is difficult to visualize. But it means that coastlines were radically different from those we

know today. Areas that are continents today were in some places shallow seas. Then much later during the early Cenozoic, Earth experienced a series of relatively short-lived but intense warming events known as **hyperthermals**. The best known is the **Palaeocene-Eocene Thermal Maximum (PETM)** around 56 million years ago when a large injection of carbon into the atmosphere-ocean system was associated with rapid global warming, temperatures increased by roughly 5-8 °C, ocean acidification took place with major environmental changes.

These examples tell us something fundamental: Earth's climate has never been fixed. But knowing that climate had changed is only the beginning. Saying that climate change is a normal feature of Earth history is scientifically important. But it can also be misleading if we stop there. A climate change occurring over millions of years is not necessarily comparable to a rapid climate perturbation occurring over decades or centuries. The

causes can also be completely different. Earth's climate has responded to changes in atmospheric greenhouse gases, volcanic activity, Earth's orbit, continental configuration, ocean circulation, ice sheets, vegetation, weathering and many interactions among these processes. The climate system is, therefore, less like a thermostat being turned up or down and more like a vast network of connected components. Change one component and others may respond.

But don't we already have enough palaeoclimate data?

Yes, we have an enormous amount of palaeoclimate data. But we do not have a perfect record of Earth's climate. Instead we have pieces of a gigantic puzzle. Ice cores tell us about ancient atmospheres. Tree rings preserve information about environmental variability. Speleothems record changes in cave environments and

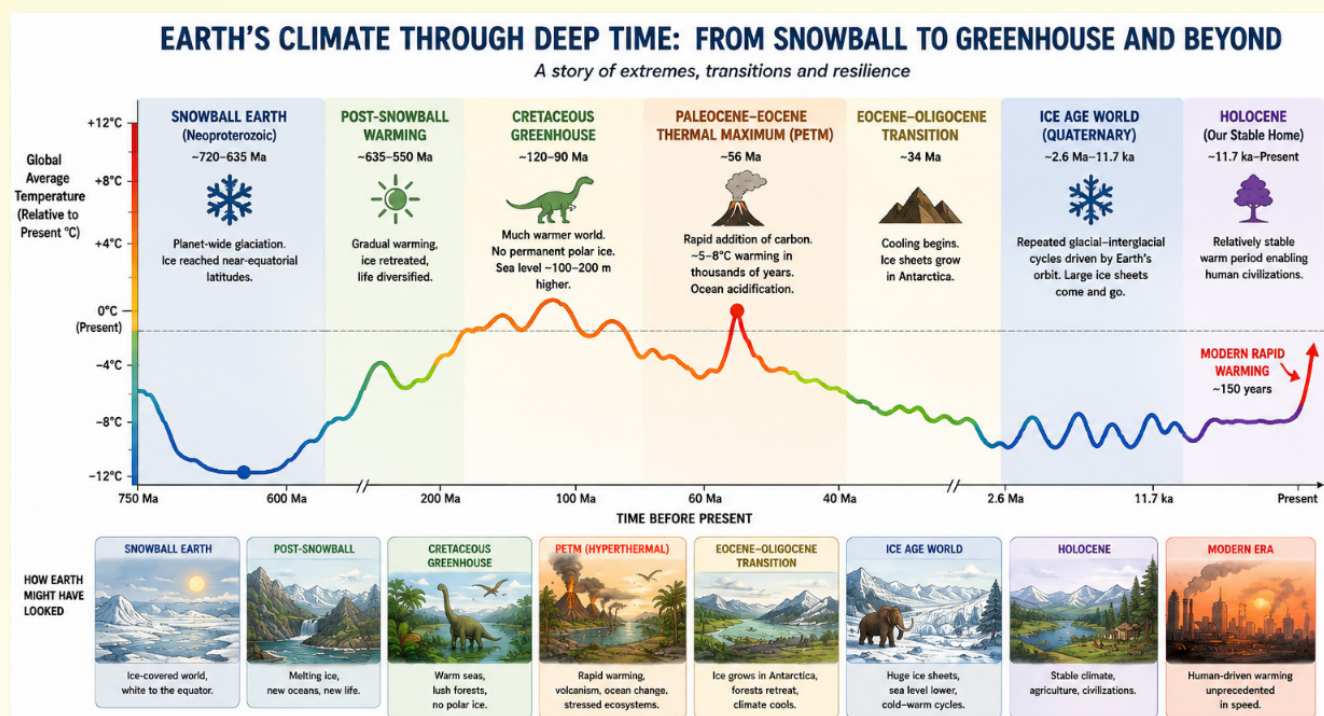


Figure 1. Schematic illustration of major climate states and transitions in Earth's climate history, from the Neoproterozoic Snowball Earth to the present. The figure is intended to illustrate the magnitude and contrasting rates of climatic change rather than provide a quantitative temperature reconstruction.

hydrology. Marine sediments preserve information about oceans and climate. Lake sediments can record changes in rainfall, erosion, vegetation and lake productivity. Fossils and pollen reveal changes in ecosystems. Even tiny magnetic minerals can preserve information about environmental processes and under suitable circumstances, the ancient magnetic field of the Earth. But these records are not evenly distributed across the planet. Some regions have hundreds of records. Others have only a handful. Some records extend back millions of years but have relatively coarse temporal resolution. Others capture relatively short intervals but at annual, decadal or even finer scales. And different proxies do not measure exactly the same thing. A pollen grain is not a thermometer. A magnetic

mineral is not a rain gauge. An oxygen isotope value is not a direct measurement of temperature. Each is a clue. The challenge of palaeoclimate science is to understand what that clue actually represents and then combine it with other evidence. A recent review of palaeoclimate data assimilation highlights exactly this problem: reconstructing past climate through both time and space remains difficult because proxy records are unevenly distributed and contain uncertainties. So the question is not simply ‘Do we have palaeoclimate data?’ We certainly do. The better question is ‘*Do we have the right data, from the right place, covering the right time interval, at sufficient resolution and with reliable chronology to answer a particular question?*’

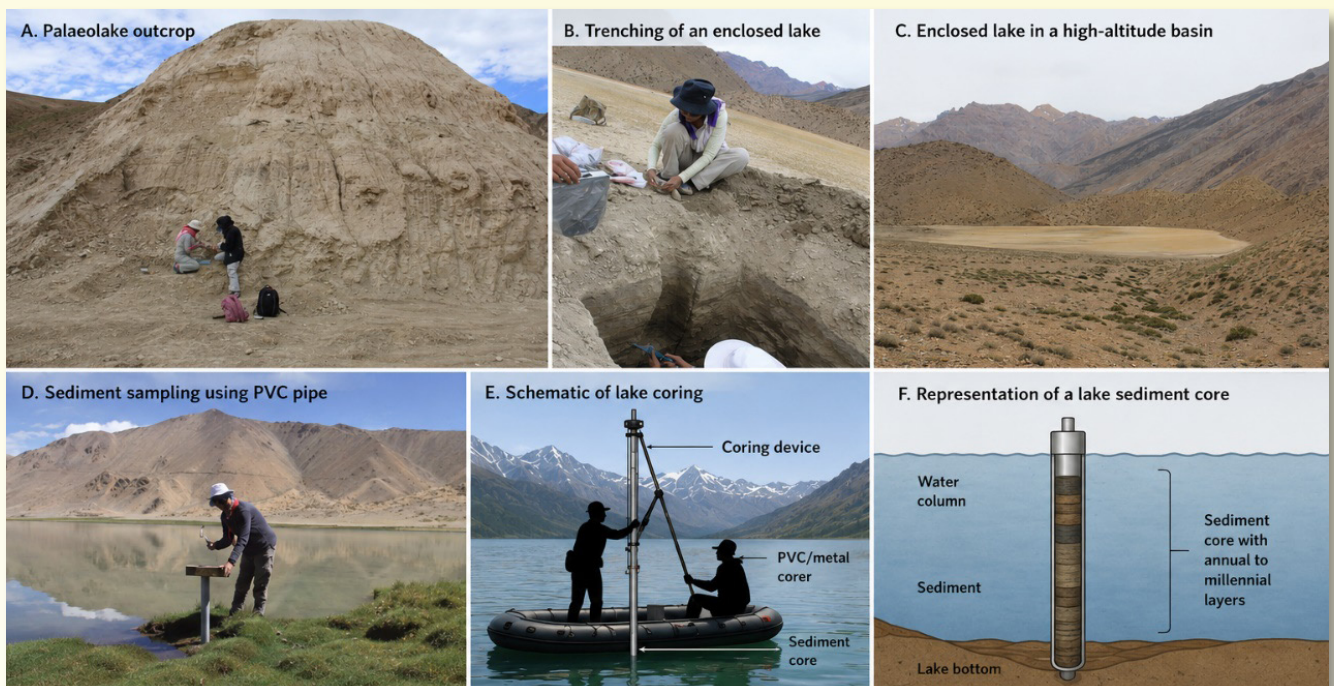


Figure 2. Natural archives of past climate preserved in Himalayan lake and palaeolake sediments. (A) Palaeolake sedimentary outcrop exposing ancient lacustrine deposits. (B) Trenching of an enclosed lake sediment sequence for stratigraphic sampling. (C) Enclosed high-altitude lake basin. (D) Sediment sampling using a PVC pipe at the lake margin. (E) Schematic representation of lake sediment coring from a floating platform. (F) Schematic representation of a lake sediment core, illustrating the accumulation of successive sediment layers that preserve a record of past environmental and climatic conditions.

Lessons from Himalaya

The Himalaya provides a beautiful example of why we cannot simply rely on a single global climate story. The Indian Summer Monsoon is not experienced in exactly the same way across the subcontinent. The Himalaya sits at the intersection of several climatic influences including the summer monsoon and winter westerlies. Its enormous elevation range also means that changes in temperature, precipitation, glaciers, vegetation and erosion can produce very different responses from one valley or basin to another. Lake sediments, therefore, become valuable natural archives. For example sediments from Tadaag Taal in Kumaun northwestern Himalaya have been used to reconstruct roughly the last 1500 years of climate variability. By combining several clues including stable isotopes, grain size and trace-element ratios, scientists reconstructed alternating periods of wetter and drier conditions. One of the most revealing episodes occurred during the Little Ice Age. Rather than being uniformly dry, the Tadaag Taal record suggests relatively wet conditions followed by a drier phase. But importantly, this pattern differs from records farther south in Central India where the Little Ice Age was predominantly dry. **The lesson is important: even a climate event with a familiar name does not necessarily produce the same response everywhere or even throughout its own duration.** Another example comes from Khajjiar Lake in Himachal Pradesh. A multi-proxy sediment record spanning roughly 4600 years combined magnetic susceptibility, carbon isotopes, geochemistry and grain size to reconstruct changes in the local environment. The record identified broad climatic phases corresponding to events such as the 4.2 ka event and Roman Warm Period while also showing considerable spatial variation and duration of climate events varied across regions when compared with other Indian records. And even older Himalayan sediments can reveal climate variability. At Goting in the Higher Central Himalaya of Uttarakhand, lake sediments spanning the Last Glacial to Early Holocene preserve evidence of changing monsoon conditions. Mineral magnetic and geochemical records identified not only

millennial-scale variability, but also centennial-scale changes between roughly 16.5 and 12.7 thousand years ago.

These records are not redundant. They are pieces of a larger picture. One tells us what happened in Kumaun. Another tells us about Himachal Pradesh. Another records conditions in the higher Himalaya. When these records are compared, an important question emerges ‘*Which climate changes were regional and which were truly widespread?*’ That is precisely why palaeoclimate scientists continue to collect new records. This regional perspective has implications for the future. If past climate changes affected different Himalayan environments in different ways, future climate change should not be expected to produce a single uniform ‘Himalayan response’. Understanding how precipitation, temperature, glaciers, vegetation, erosion and hydrology have interacted in the past can help identify which parts of the system are particularly sensitive to change. Such knowledge can contribute to better-informed approaches to water-resource management, ecosystem conservation and climate adaptation in mountain regions.

There is another problem. Imagine a climate event that lasts only a few decades. Now imagine taking one sediment sample every 200 years. You might completely miss the details. You could see that “something happened,” but not when it began, how rapidly it developed, how long it lasted or how quickly the system recovered? This is especially important when studying rapid climatic changes. For example, Methane is a powerful greenhouse gas, but it is relatively short-lived in the atmosphere compared with carbon dioxide. The IPCC estimates its total atmospheric lifetime at about 9 years and its perturbation lifetime at approximately 11.8 ± 1.8 years. That does not mean that every palaeoclimate record must have a 12-year sampling interval. But it does illustrate an important principle: if we want to investigate a climate perturbation that developed over decades, a record sampled only every century or two may not contain enough information to resolve its dynamics.

And sampling resolution is only half the story. Suppose we collect a sample every ten years but our age

model is uncertain by 100 years. We have high sampling density but poor chronological precision. This is why palaeoclimate scientists care so much about both resolution and chronology. The goal is not simply to collect more samples. It is to collect information at a resolution appropriate to the scientific question and to know when those samples were deposited.

When the model and the proxy start talking!

There is an even deeper reason for studying the past. We cannot experimentally change the Earth's climate. We cannot remove an ice sheet and see what happens. We cannot increase atmospheric carbon dioxide for thousands of years and wait to observe the consequences. We cannot reproduce the conditions of the Last Glacial Maximum (LGM) in a laboratory. But, Earth has already experienced these changes. In that sense, the geological past provides something extraordinary: natural experiments. The LGM is a particularly useful example. Climate scientists can run models under LGM boundary conditions. Around 20,000 years ago, large ice sheets covered much of northern North America and Eurasia. The planet was substantially colder than today. We have geological and biological evidence of this different climate state and scientists can also simulate it using climate models. The interesting question is not simply 'Was the LGM cold?' We already know that. The interesting questions are 'How cold was it? Where was it coldest? How did rainfall change? How did the oceans respond? How large were the ice sheets? And can our climate models reproduce the patterns preserved in geological archives?' Studies comparing LGM proxy reconstructions with climate simulations show that models and observations broadly agree on many large-scale features, while regional mismatches remain important areas for further investigation. This is one reason ancient climates matter for the future. A model that can reproduce a climate that we know existed in the past has passed one kind of test. A model that fails to reproduce the past tells us where we still need to improve. Research on model-proxy comparisons has shown that bringing the two together can help

identify uncertainties in both datasets and models and can ultimately improve our understanding of climate behaviour and future projections.

And what about the less obvious signals?

Sometimes palaeoclimate scientists look for clues that seem, at first, to have little to do with climate. For example rocks and sediments can preserve evidence of Earth's ancient magnetic field. Palaeomagnetic research can reconstruct changes in the direction and intensity of the geomagnetic field through geological time. Some studies have reported intriguing temporal associations between geomagnetic variability and climate particularly in Quaternary records. Whether such relationships represent a genuine physical connection, a shared external forcing, or an artefact of the way records are produced and dated remains an open scientific question. A relationship observed in one set of records may disappear when tested in another. It may be influenced by chronology, sedimentation, preservation, normalization or other characteristics of the archive. Or it may reflect a genuine physical interaction. That uncertainty is not a reason to stop investigating. It is precisely what makes it a scientific question. The goal is not to assume that the magnetic field controls climate. The goal is to ask '*Is there a statistically reproducible relationship between geomagnetic variability and independent climate records, and does that relationship survive when tested across different geological intervals and different archives?*' That is a very different question. And sometimes the most valuable result of such a study is discovering that an attractive pattern does not survive a rigorous test. Science advances not only when hypotheses are confirmed, but also when attractive explanations are shown to be inadequate.

So, are palaeoclimate scientists simply studying the same warm and cold climates again and again? Perhaps, if the goal were only to produce another temperature curve. But that is not really what palaeoclimate science is about. We study the past because Earth has already conducted experiments that humans cannot conduct themselves. It has frozen. It has warmed.

It has lost and gained enormous ice sheets. It has changed atmospheric composition. Its oceans have reorganised. Its ecosystems have expanded, contracted and transformed. And through all of this, Earth has left fragments of the evidence behind. Our job is to learn how to read those fragments. *Sometimes the missing piece is geographical: we need records from a region that has been poorly studied. Sometimes it is temporal: we need higher-resolution records to capture rapid changes. Sometimes it is mechanistic: we know that something changed, but not why. Sometimes it is methodological: different proxies tell different stories and we need to understand why. And sometimes the answer lies in bringing two seemingly unrelated archives together.*

This is why palaeoclimate research is not a finished story. It is an unfinished one.

Climate has always changed. But that is not the end of the story. It is the beginning of a much more important question. How does the Earth respond when it changes? For example, the Gya valley in Ladakh offers a glimpse of that response where

climate change propagates through the Earth system. A change in temperature or precipitation can alter glaciers and snow, which alter rivers; rivers transport sediment, sediment reshapes channels and changing landscapes influence ecosystems in return. The response is not linear and it is rarely controlled by climate alone. The Gya valley shows that climate variability can be expressed through **glacier-river-sediment-landscape interactions**, leaving physical evidence in the mountains themselves.

So, palaeoclimate records reminds us that Earth's climate system is capable of moving between states far more different from one another than the relatively stable climate in which human civilisation developed. So yes- climate change is a norm in Earth's history. *The questions are How? Why? How fast? How far? And with what consequences?* Understanding these questions from Earth's own geological experiments may help us make better decisions about the changing world in which we live.

That is why scientists are still digging into ancient mud, studying fossils, measuring isotopes, examining magnetic minerals and reconstructing climates that

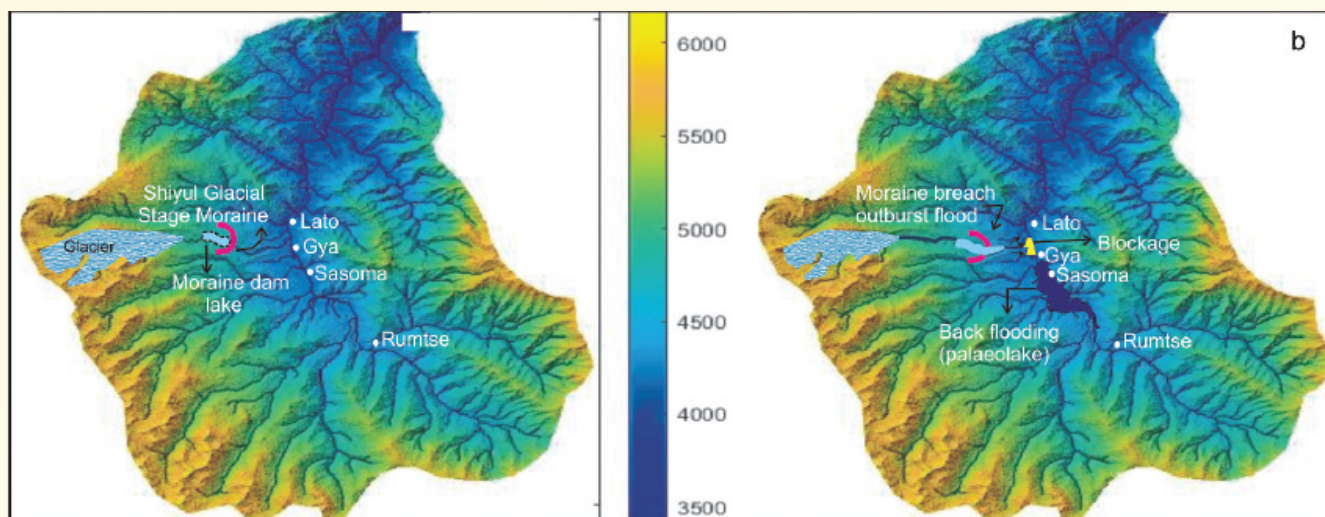


Figure 3. Schematic representation of moraine dammed lake along the tributary valley followed by moraine breach outburst and damming of the main Gya river valley and subsequent backflooding leading to the formation of palaeolake.

disappeared thousands, millions or even hundreds of millions of years ago. We are not simply trying to understand a world that is gone. We are trying to understand the rules of the world that remains!

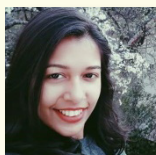
Further Readings

NASA Earth Observatory — Paleoclimatology: Understanding the Past to Predict the Future
Hoffman & Schrag (2002) — The Snowball Earth hypothesis: Testing the limits of global change.
Tierney et al. (2025) — Advances in Paleoclimate Data Assimilation
Schmidt (2010) — Enhancing the relevance of palaeoclimate model/data comparisons for assessments of future climate change
Miller et al. (2005) — The Phanerozoic record of global sea-level change
McInerney & Wing (2011) — The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon

Cycle, Climate, and Biosphere with Implications for the Future

Kaushik et al. (2023) — Paleoclimatic reconstruction of northwest Himalaya since CE 475 using lake sediments from Tadaag Taal, Kumaun, India.
Kotlia et al. (2024) — Mid-late Holocene climatic reconstruction using core sediments from Khajjiar Lake, Himachal Pradesh, India.
Juyal et al. (2009) — Reconstruction of Last Glacial to early Holocene monsoon variability from relict lake sediments of the Higher Central Himalaya, Uttarakhand, India.
Nag et al. (2022) — Geomorphological and sedimentological evidences of palaeo-outburst flood events from Tanglang La–Gya catchment of River Indus, Ladakh, India.
Gallet et al. (2005) — Does Earth's magnetic field secular variation control centennial climate change?

About author



Dr Debarati Nag is a DST WISE-Post Doctoral fellow at Palaeomagnetic Laboratory, BSIP, Lucknow. Her research focuses on understanding palaeoclimate of the Cenozoic Era, developing stratigraphic framework using palaeomagnetic records and understanding evolution of the Earth's magnetic field.

Climate Change at the 4.2 ka (4.5–3.9 ka) and the fall of the Harappan Civilization: A critical review

Tarannum Jahan and Mohammad Firoze Qamar

PROLOGUE

THE role of climate variability in the expansion and collapse of the Harappan Civilization in South Asia has been a subject of intense research and debate among archaeologists, Quaternary climate scientists, meteorologists, climatologists, historians, geographers, archaeobotanists, and anthropologists. Moreover, high-resolution palaeoclimatic studies have challenged the previous perspectives attributing societal collapses solely to socio-political and economic factors. These studies have revealed that periods of abundant rainfall, resulting from climate amelioration and/or due to seasonality: Winter vs. Summer precipitation, often coincided with the peak of socio-economic, cultural, and technological advancements in various civilizations. Conversely, abrupt climatic changes or rapid climatic changes, such as prolonged droughts, led to the destruction of irrigation systems, agricultural devastation, and widespread famines. These climatic disruptions triggered cultural adaptations, migrations, and sometimes even the collapse of entire civilizations. Climate forcing, particularly solar variability, played a primary role in repeated societal displacements, migrations, and deurbanization across different regions in the past. The depletion of water resources triggered the general demographic shift vis-à-vis the 4.2 ka event. The displacement was a response to a weakened Summer Monsoons of South Asia (Indian Summer Monsoon).

THE '4.2 KA EVENT'

The Holocene (~11.7 ka to Present; ka = calibrated kilo annum: thousand years ago: B.P.; cal kyr BP, where B.P. stands for Before Present, with present being the year 1950), has been divided by the International Commission on Stratigraphy (2018) into three Ages/Stages: Early Holocene (11.7–8.2 kyr BP), Middle Holocene (8.2–4.2 kyr BP;), and Late Holocene (4.2 kyr BP to Present;). The Holocene Epoch represents the most recent Geological Epoch and the current interglacial stage (Walker et al., 2019).

The 4.2 ka event was an Abrupt Climate Change (ACC) event (which occurred during 4.5 to 3.9 ka), marking the boundary of the Middle and Late Holocene and the onset of the Meghalayan Age, and influenced the development of human civilizations (Figure 1a, 1b) (Mayewski et al., 2004; Wang et al., 2011). The occurrence of Rapid Climate Change (RCC) or ACC events, such as the Heinrich 1 event, the Younger Dryas (YD) event, and the 8.2 ka and 4.2 ka events, which were driven by large-scale reorganizations of the atmospheric and oceanic circulation (Bakke et al., 2009; Sun et al., 2018), disrupted the trend of increasing global temperatures since the Last Glacial Maximum (~20, 000 yr BP) (Broecker, 2003). The 4.2 ka event is characterized by pronounced cooling in high latitudes and intensified aridification in middle and low latitudes (Bond et al., 2001; Mayewski et al., 2004; Booth et al., 2005; Walker et al., 2012). It is commonly described as a drought lasting for two to

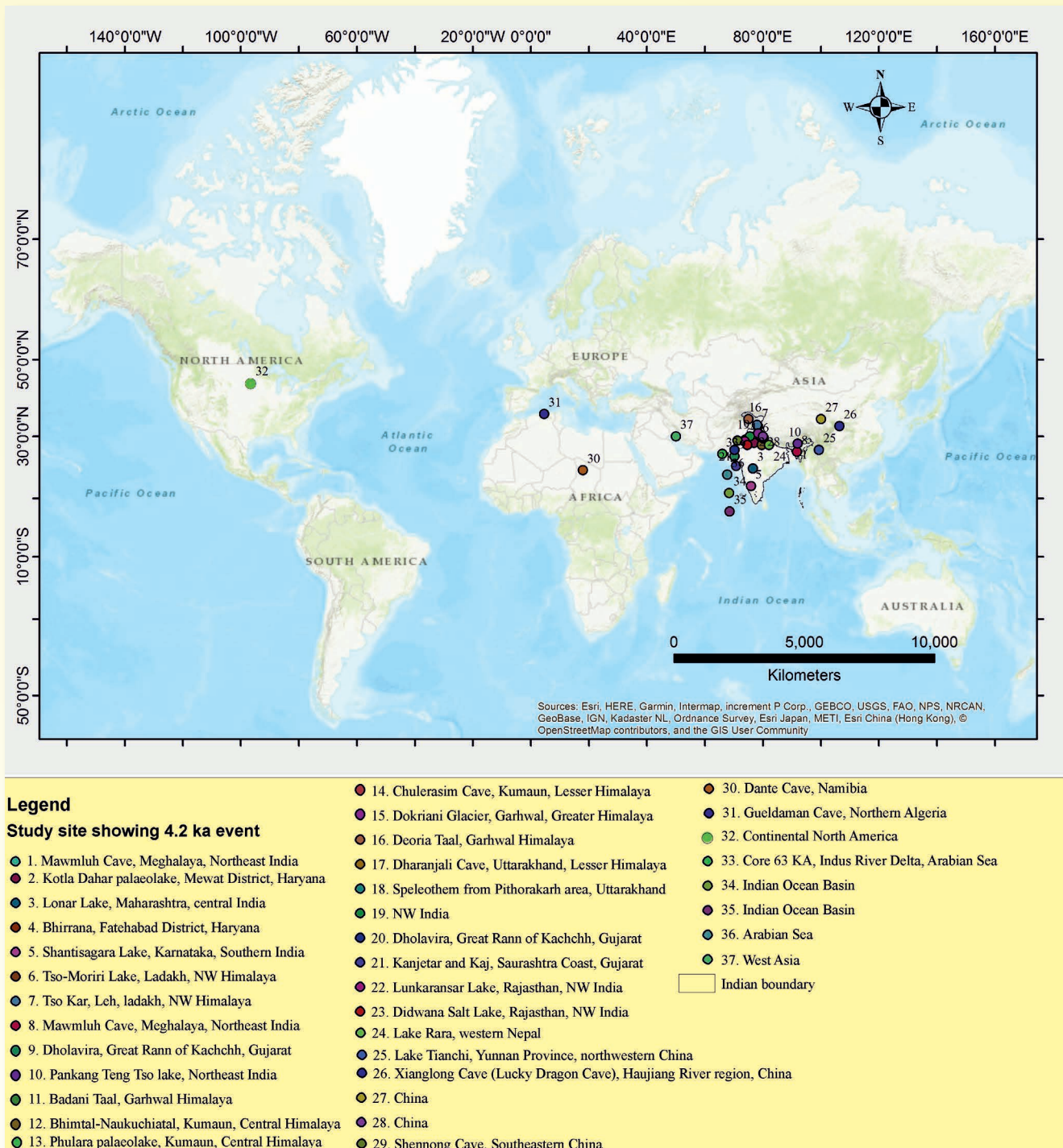


Figure 1a. World map (including India) showing the study site, mentioning the record of the ‘4.2 ka event’. For interpretation of the references to colour in this figure legend, the reader is advised to see the web version of this review article.

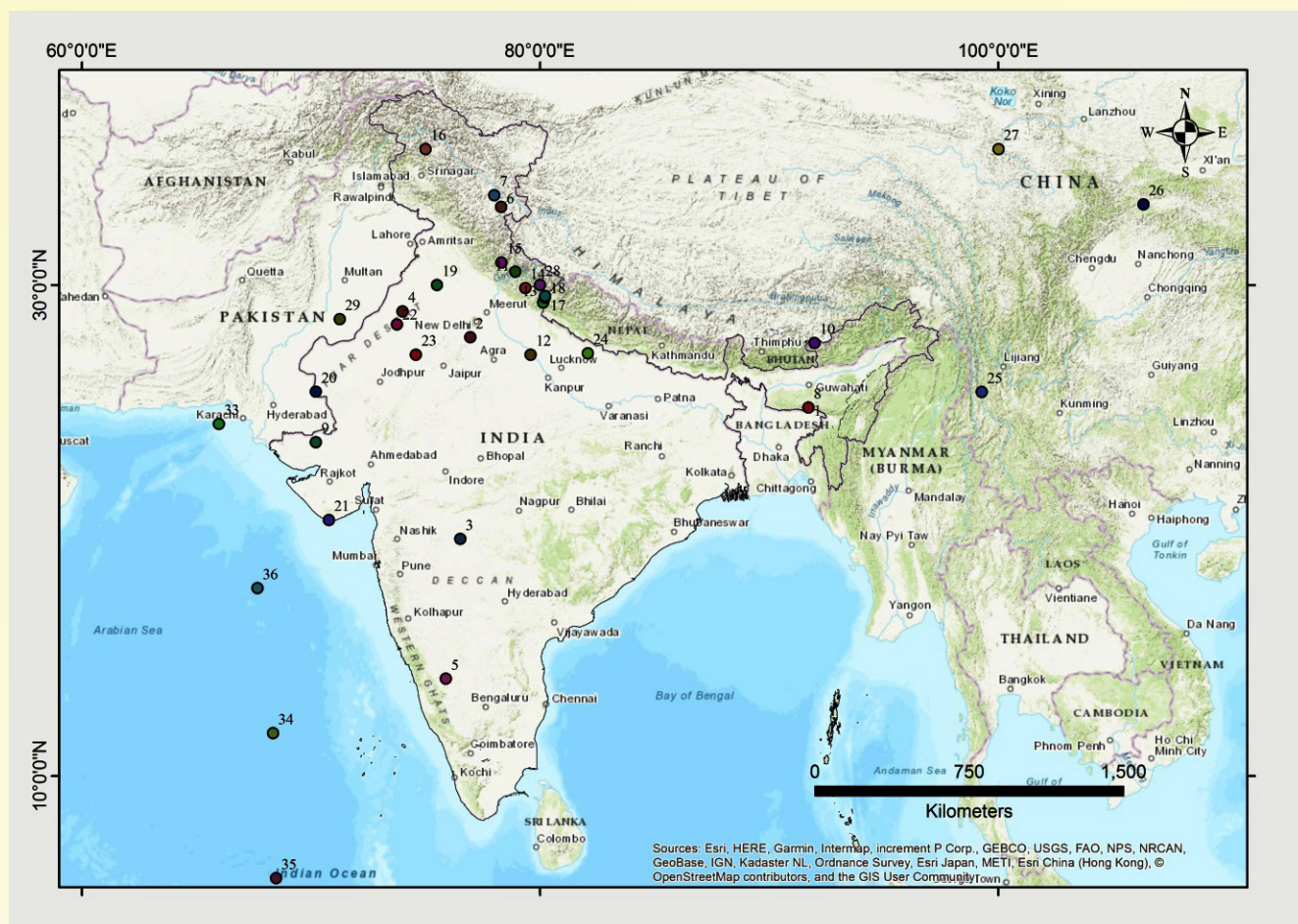


Figure 1b. Map of India (zoomed in) showing the study site, mentioning the record of the ‘4.2 ka event’. For interpretation of the references to colour in this figure legend, the reader is advised to see the web version of this review article.

three centuries (Berkelhammer et al., 2012; Dixit et al., 2014b; Nakamura et al., 2016).

The Mawmluh Cave speleothem located in Meghalaya, India, serves as the Global Stratotype Section and Point (GSSP) for this Age, whereas the Mount Logan ice core in Canada serves as the global auxiliary stratotype (Walker et al., 2012; Head and Gibbard, 2015; Walker et al., 2018; Walker et al., 2019). Notably, the 4.2 ka event within the Summer Monsoons of South Asia domain has been detected through $\delta^{18}\text{O}$ measurements of speleothems in Mawmluh Cave, Meghalaya in Northeast India (Berkelhammer et al., 2012; Kathayat et al., 2018). This

record was instrumental in defining the Meghalayan Age, and establishing the event as the formal boundary between the Middle (Northgrippian Age) and Late Holocene (Meghalayan Age) on a global scale (Walker et al., 2018). The climatic anomaly known as the “4.2 ka event” between 4.2 and 3.9 thousand years ago (ka BP) has garnered significant research attention due to its multi-decadal to century-scale duration (Fleitmann et al., 2003, 2009; Li et al., 2018; Railsback et al., 2018; Dutt et al., 2018; Lin et al., 2022; Giesche et al., 2023). The 4.2 ka event has been documented in various proxies, such as fossil pollen (Singh, 1971; Singh et al., 1972, 1990; Possel, 1997; Porinchu et

S. No.	Name	References
Seven names are essentially synonymous		
1.	4.2. ka event	Staubwasser et al., 2003; Booth et al., 2005; Arz et al., 2006; Zhang et al., 2010; Zhou et al., 2017; Giesche et al., 2023
2.	4.2 ka BP event	Staubwasser et al., 2003
3.	4.2 event	Arz et al., 2006
4.	4200 cal. BP event	MacDonald, 2011
5.	4200 BP event	Riehl, 2009
6.	4.2 ka cal. BP event	Wiener, 2014
7.	the so-called '4.2 ka event	Magny et al., 2009
Five names with different meaning		
8.	4.2 ka aridification event	Walker et al., 2012; Head and Gibbard, 2015
9.	4,000 BP event	Perry and Hsu, 2000
10.	Holocene Event 3	Wu and Liu, 2004
11.	~4000 cal. Yr BP event	Liu and Feng, 2012
12.	4.2 ka BP megadrought	Weiss, 2016
Other synonyms		
13.	2200 BC event	Helama, 2024
14.	2200 BCE event	
15.	4200 BP event	
16.	4200 cal BP event	
17.	4.2 kyr event	
18.	4.2 kyrBP event	
19.	4.2 kyr cal BP event	
20.	4.2 kya event	
21.	"Bond 3 climate event"	
22.	"Holocene event 3"	

Table 1. Various names (synonyms) of the '4.2 ka event' used in the scientific literature (after Railsback et al., 2018 and Helama, 2024).

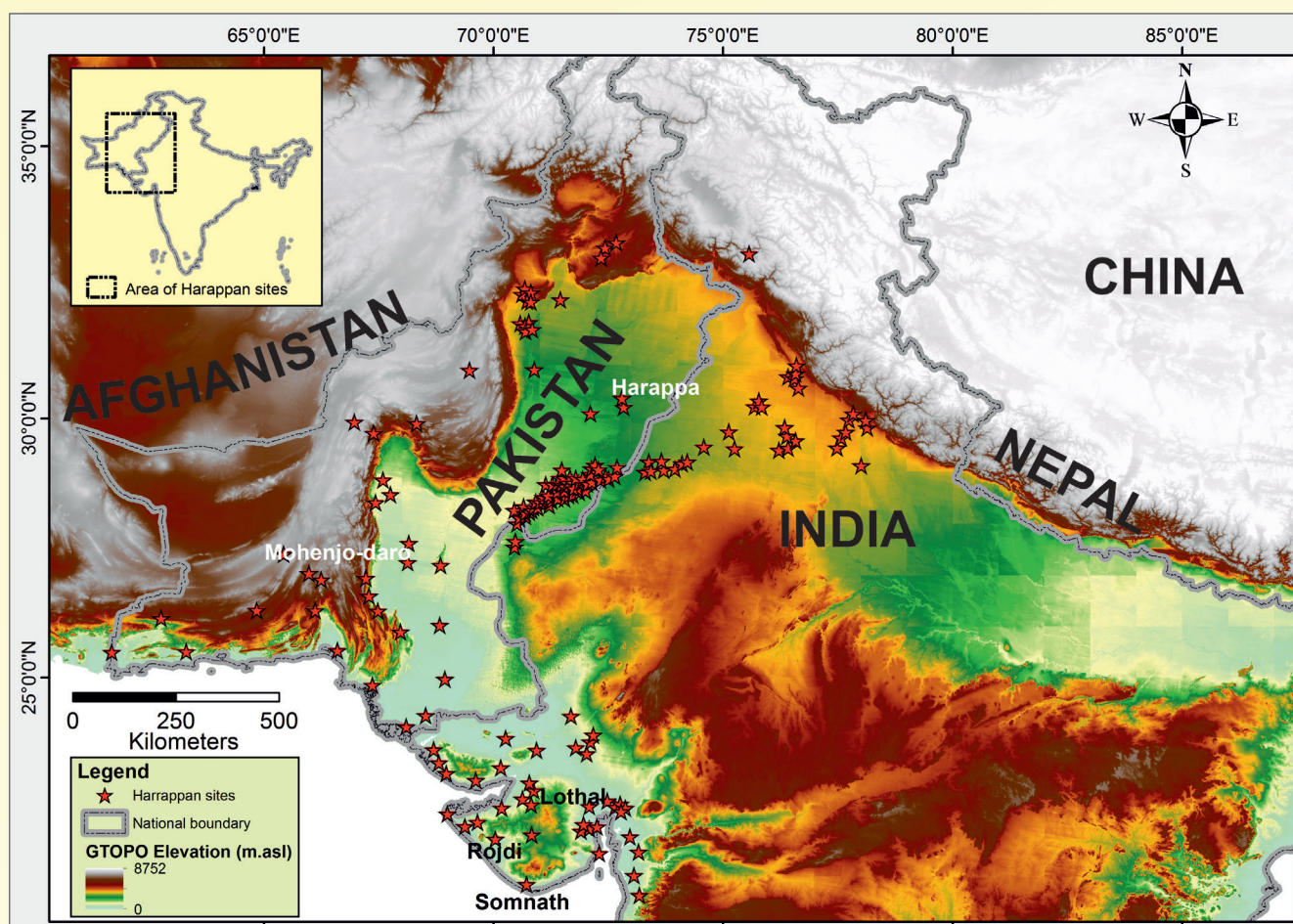


Figure 2. Distribution of Harappan sites in domains of the Indus Valley in India and Pakistan. The Harappan sites (“red star”) have been extracted from Possehl et al. (2002b) on ArcGIS 10.3 software and superimposed on GTOPO SRTM data. For interpretation of the references to colour in this figure legend, the reader is advised to see the web version of this review article.

al., 2026), $\delta^{18}\text{O}$ record of gastropod aragonite (Dixit et al., 2014), animal teeth bone phosphate (Sarkar et al., 2016), archaeobotanical and geochemical analyses, stable carbon isotope ($\delta^{13}\text{C}$) measurements (Pokharia et al., 2017), U–Pb zircon dating (Clift et al., 2012), and fluvial morpho-dynamics (Giosan et al., 2012) of marine sediments (Cullen et al., 2000; Arz et al., 2006), lake sediments (Ohlendorf et al., 2014; Nakamura et al., 2016), glacial ice (Thompson et al., 2002; Menounos et al., 2008), and stalagmites (Bar-Matthews et al., 1999; Berkelhammer et al., 2012) originating from both the Northern and Southern Hemispheres (Drysdale et al.,

2006; Ohlendorf et al., 2014), as well as the Eastern and Western Hemispheres (Figures 1a, 1b) (Berkelhammer et al., 2012; Booth et al., 2005).

The estimates of the duration of the 4.2 ka event vary substantially, from ~130 years (Li et al., 2006; Sharifi et al., 2015), to as long as ~600 years (Zanchetta et al., 2016; Psomiadis et al., 2018), as well as the start and end times also differ (Liu et al., 2013; Railsback et al., 2018). Lin et al. (2022) suggested that the onset of the 4.2 ka event in East Asian and Indian Monsoon region was similar (mainly at ~4.2 ka; within the dating error), whereas its duration in the Indian Monsoon

Kenoyer (1998)			Possehl (2002)		Dutt et al. (2019)		
Period	Phase	Years B.C.	Years B.C. [§]	Stage	S. No.	Phase	B.C.E. [§]
1 A/B	Early Harappan/ Ravi	c. 3300- 2800	7000-5000 and 5000- 4300	Beginning of village farming communities and pastoral societies (two non-contemporaneous phases)	1	Pre-Harappan	7000-3200
2	Early Harappan/ Kot- Diji	c. 2800- 2600	4300-3800 and 3800- 3200	Developed village farming communities and pastoral societies (two non-contemporaneous phases)	2	Early Harappan	3200-2600
3	Harappan	c. 2600- 2450	3200-2600	Early Harappan (four contemporaneous phases)	3	Mature Harappan	2600-1900
3A					4	Late Harappan	1900-1000
3B							
3C							
4							
5							
3A	Harappan	c. 2600- 2450	3200-2600	Early Harappan (four contemporaneous phases)	3	Mature Harappan	2600-1900
3B	Harappan	c. 2450- 2200	2600-2500	Early Harappan/Mature Harappan Transition	4	Late Harappan	1900-1000
3C	Harappan	c. 2200-1900	2500-1900	Mature Harappan (five contemporaneous phases)	5	Early Iron Age	1000-500
4	Harappan/ Late Harappan Transition	1900- ?1700	1900-1000	Post-urban Harappan (several non-contemporaneous phases)			
5	Late Harappan (Cemetery H)	?1700- 1300	1000-500	Early Iron Age of northern India and Pakistan Painted Grey Ware			

Table 2. Chronological account of the Harappan Civilization* (modified after Madella and Fuller, 2006). Also, the chronology of the Harappan Civilization, proposed by Kenoyer (1998), Possehl (2002) and Dutt et al. (2019), have also been provided in the table.

[§]B.C.E. (B.C.) = Before Common Era

* Harappan Civilization= Early Harappan Phase: 3000–2600 BC (BCE henceforth) Mature Harappan Phase: 2600–2000 BCE (2600-1900 BCE:

https://en.wikipedia.org/wiki/Indus_Valley_Civilisation; 09/05/23); Late Harappan Phase: 2000–1200 BCE (Pokharia and Srivastava, 2013)

* Harappan Civilization = Early Harappan Phase: 3000–2500 BCE; Mature Harappan Phase: 2500–2000 BCE; Late Harappan Phase: 2000–1200 BCE (Pokharia et al., 2014) n

* Harappan Civilization = Early Harappan Phase: 3300–2600 BCE; Mature Harappan Phase: 2600–2000 BCE; Late Harappan Phase: 2000–1700 BCE (Farooqui et al., 2013)

* Harappan Civilization (in kyr BP) = Early Ravi Phase: ~5.7–4.8 kyr BP; Transitional Kot-Diji phase: ~4.8–4.6 kyr BP; Mature phase: 4.6–3.9 kyr BP; Late declining (painted Grey Ware) phase: 3.9–3.3 kyr BP (Kenoyer, 1998; Wright et al., 2008; Dikshit and Mani, 2012).

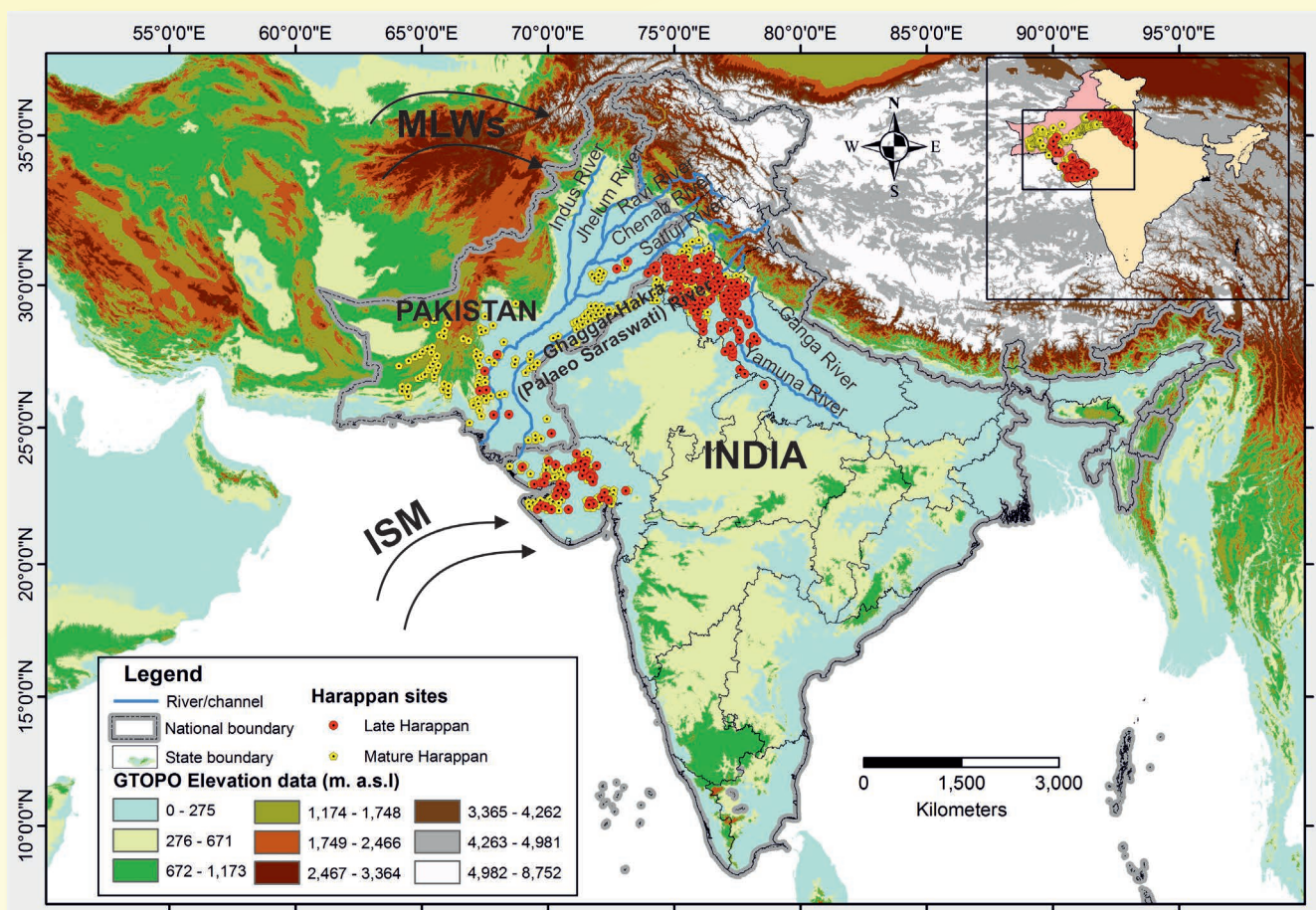


Figure 3. The GTOPO 30 digital elevation map (DEM) of India, showing the Mature (yellow polygon) and Late Harappan (red circle) sites (after Possehl, 1996, 2002b; Dutt et al., 2018, 2019). For interpretation of the references to colour in this figure legend, the reader is advised to see the web version of this review article. Source: The figure has been prepared using ArcGIS 10.3 (Global 30 Arc-Second Elevation (GTOPO30) Digital Object Identifier (DOI) number: /10.5066/F7DF6PQS.

region was slightly longer than elsewhere. Hence, it (i.e. the “4.2 ka event”) is an asynchronous climate anomaly. Owing to its widespread occurrence and broad effects, it has been termed a “global megadrought” (Weiss et al., 2016) or an “aridification event” (Walker et al., 2012; Head and Gibbard, 2015), and is officially recognized as the stratigraphic marker (Global Stratotype Section and Point: GSSP in a stalagmite of Mawmluh Cave from Meghalaya, India: International Commission on Stratigraphy: ICS) between the Middle and Late Holocene (Walker et al., 2012, 2018; Head and Gibbard, 2015; Toth and Aronson, 2019; Shankar, 2021).

Various names were proposed time-to-time by different workers to denote the ‘4.2 ka event’. For example: Weiss (2016) proposed the term “global megadrought” to describe the widespread occurrence of the ‘4.2 ka event’ in both the Northern and Southern Hemispheres (Drysdale et al., 2006; Ohlendorf et al., 2014), as well as in the Eastern and Western Hemispheres (Berkelhammer et al., 2012; Booth et al., 2005). However, alternative names have also been proposed for this climatic anomaly, each carrying its own chronological or climatological implications (Table 1). Most of these terms suggest an event or pulse with a recognizable beginning and end (Cullen

et al., 2000; Thompson et al., 2002; Stanley et al., 2003; Drysdale et al., 2006; Prasad and Enzel, 2006; Regattieri et al., 2014; Sharifi et al., 2015), whereas other records indicate a shift or transition, representing a one-time unidirectional change in conditions (Shulmeister and Lees, 1995; Haug et al., 2001; Kröpelin et al., 2008; Hardt et al., 2010; Zhang et al., 2013; Ruan et al., 2016; Shi et al., 2017). These are to name but a few. The other synonyms of the '4.2 ka event', however, have been presented in Table 1 (Railsback et al., 2018; Helama, 2024).

The cool-dry climate and weak Indian Summer Monsoon (ISM) during the 4.2 ka event is attributed to the southward shift of the Inter Tropical Convergence Zone (ITCZ), which occurs in response to decreasing summer insolation in the Northern Hemisphere. The abrupt ISM weakening at the 4.2 ka has been linked to the stronger phase of El Niño and a shift of the Indian Ocean Dipole (IOD) to a strong negative state. As one of the most pronounced Holocene cooling events, the 4.2 ka event provides a natural experiment to investigate the teleconnections between the ISM, as well as various forcing factors, such as the El Niño, Inter Tropical Convergence Zone (ITCZ), Indian Ocean Dipole (IOD), and Summer Insolation (SI) in the low-latitude region.

HARAPPAN CIVILIZATION

The Harappan Civilization, also known as the Indus Valley Civilization (Giosan et al., 2012; Dutt et al., 2019), was a highly documented, urbanized, advanced, and widespread ancient civilization flourished during the Bronze Age around 5000 years ago (BP) (Figures 1 & 2; Tables 2 & 3) (Sarkar et al., 2016; Dutt et al., 2018, 2019; Sengupta et al., 2020; Kathayat et al., 2022 and references cited therein). It developed in the arid outer regions influenced by the Summer Monsoons of South Asia. The Harappan Civilization lasted from 3300 BCE to 1300 BCE (BCE stands for Before Common Era) (~5.3 to 2.3 kyr BP), with its Mature Phase occurring from 2600 BCE to 1900 BCE (~4.6 to 2.9 kyr BP) (Wright, 2009). The chronological account of the Indus Valley Civilization (IVC) has been given in Table 2; however.

The geographical extent of the Harappan Civilization ranged from Sutkagen-Dore in the west (near present-day Iran and earlier of the western-most of Makran Coast, Pakistan) to Alamgirpur in the east (Saharanpur District of Uttar Pradesh, India), Manda in the north (Jammu and Kashmir, India), and Daimabad in the south (Maharashtra, India) (Possehl, 2002; Pokharia and Srivastava, 2013; Farooqui et al., 2013; Pokharia et al., 2014). The major urban centers (five) of the Harappan Civilization were Harappa (in western Punjab, Pakistan), Mohen-jo-Daro (in the lower Indus Valley, Pakistan), Ganeriwala (in the Cholistan Desert, Bahawalpur District, Punjab, Pakistan), Dholavira (in western Gujarat), and Rakhigarhi (in Haryana) (Wright, 2009). However, there were more than a thousand Mature Harappan sites spread over an area of ~1.5 million km² in modern-day India, Pakistan, and Afghanistan (Possehl, 2002; Vahiya and Yadav, 2011). Among the hundred excavated or known settlements (Possehl, 2002; Singh, 2008), about 80% of them were located around the Ghaggar-Hakra river system or the paleo-Saraswati channel, therefore, the Harappan Civilization is also called as the Saraswati Civilization (Kalyanaraman, 2008; Sarkar et al., 2016; Laskar and Bohra, 2021; Quamar et al., 2024) (Figures 2 & 3; Tables 2 & 3). Moreover, Saraswati River region(s) are traditionally regarded as the home of the Vedas, which has been proven to be larger and older than Harappa and Mohen-jo-Daro (which are on the Indus River). Also, Rakhigarhi (in Haryana, India) is the largest Harappan site, therefore, it would be more accurate to associate the Harappan Civilization with the Rakhigarhi, rather than Harappa, which also better reveals the geographical connections of the very site to later India, and its prime historical regions. Additionally, more than 63% of the archaeological sites are located in the banks of the River Saraswati and River Drishadwati, and around 21% of the archaeological sites are located in the banks of River Indus. Therefore, the statistics of the site distribution provide us the indication that Vedic Saraswati Civilization is appropriate. Therefore, it is suggested to call the Harappan Civilization as the Vedic Saraswati Civilization (<https://www.firstpost.com/opinion/not-harappan-civilization-but-vedic>

saraswati-civilization-13562332.html; 03.01.2024; 05.02.2024; Not Harappa... but Indus-Saraswati Civilization! indiatimes.com; 05.08.2024).

The Harappan Civilization showcased remarkable achievements in various aspects, including well-planned architecture, water storage, pottery, drainage systems, scripture, agriculture, and marine trade, despite its vast territorial expanse (Possehl, 1997; Giosan et al., 2012). Pokharia and Srivastava (2013) were of the view that the Harappan Civilization demonstrated a high level of technological advancements in town planning, architecture, ceramics, metallurgy, bead styles, terracotta, seals, intensive agriculture, long-distance trade, uniform script, and standardized weights and measures. The urban centers of the Harappan Civilization, furthermore, exhibited a notable degree of uniformity in brick size (following a 1×2×4 ratio) and measurement standards, although regional variations were also observed (Possehl, 2002; McIntosh, 2007; Vahia and Yadav, 2011). The transformation from hunter-gatherer societies to village farming communities marked the Pre-Harappan phase along the western boundary of the Harappan Civilization settlements. During the Early Harappan phase, village farming communities expanded, population increased, and new areas to the south and east were settled, giving rise to incipient urbanization. The Early Harappan phase shows settlement expansion, mud brick houses with advanced material culture including arrow heads, rings and bangles of copper; beads of carnelian, jasper, and shell; bull figurines; chert blades; terracotta bangles, etc. (Lal et al., 2004; Rao, 2006, Rao et al., 2005; Sarkar et al., 2016). The Mature Harappan phase witnessed the establishment of several urban and village settlements, characterized by a highly stratified society, agricultural growth, flourishing trade, and remarkable architectural features, such as a gridded pattern of streets, houses made of baked bricks, and an advanced drainage system. The early Mature to Mature Harappan phases yielded ceramics with geometric, floral and faunal motifs; steatite bull seals; beads of semi-precious stone, shell and terracotta; animal figurines; bangles of faience and shell; copper bangles, chisels, rings, rods, etc. (Rao, 2006, Rao et al.,

2005; Sarkar et al., 2016). This period is often referred to as the "Golden Age" of the Harappan Civilization (Possehl, 2002; Madella and Fuller, 2006; McIntosh, 2007; Vahia and Yadav, 2011).

DRIVERS OF THE FALL OF THE HARAPPAN CIVILIZATION

The enigmatic displacement/migration, decline and/or fall of one of the most advanced Bronze Age civilizations (i.e. the Harappan or Indus Civilization) at 4.2 thousand years ago (ka) has been a subject of intense debate among Quaternary climate scientists, meteorologists, climatologists, archaeologists, historians, archaeobotanists, and others for over a century (Figures 1-3; Tables, 1-3) (Khan, 1968; Costantini et al., 1981, 1987, 1990; Kenoyer, 1991, 1997, 1998, 2008; Mughal, 1996, 1997; von Rad et al., 1999; Satubwasser et al., 2002; Staubwasser et al., 2003; Possehl, 2002; Schuldeurein et al., 2004; Gupta et al., 2006; Wright, 2009; Gangal et al., 2010; MacDonald, 2011; Vahia and Yadav, 2011; Sinha et al., 2020; Khan et al., 2024; Ngangom and Thakkar, 2024; Helama, 2024, and references cited therein). To unravel this hypothetical uncertainty and to comprehend the complex socio-climatological linkages, multiple perspectives from several schools of thought have emerged. Archaeologists have proposed that changes in socio-economic conditions (Possehl, 2002), agricultural strategies (Madella and Fuller, 2006), foreign invasions, and conflicts (Wheeler, 1968), as well as changes in the courses of the Yamuna and the Sutlej rivers (Yashpal et al., 1980; Agrawal and Sood, 1982) and spread of infectious diseases (Robbins Schug et al., 2013) were major driving factors responsible for the decline of the Harappan Civilization. However, the absence of evidence of weapons and warfare challenges the hypothesis of a foreign invasion or internal conflicts (Possehl, 2002; McIntosh, 2007). Additionally, scientific studies do not support significant changes in the Yamuna watershed since the Last Glacial Maximum (~20,000 yr BP) (Clift et al., 2012). While there is debate regarding the shifting of the Sutlej River, it occurred during the period of approximately 10–8 ka,

S. No.	Harappan Civilization* in India	
Eastern Region**		
1	Kalibangan	Ganganagar District, Rajasthan
2	Rohira and Mahorana	Sangrur District, Punjab
3	Sanghol	Ludhiana District, Punjab
4	Banawali and Kunal Farmana	Hissar District, Haryana
5	Balu	Kaithal District, Haryana
	Farmana	Rohtak District, Haryana
7	Hulas	Saharanpur District, Uttar Pradesh
8	Alamgirpur	Meerut District, Uttar Pradesh
Southern Region***		
9	Rojdi	Rajkot District, Saurashtra region, Gujarat
10	Lothal	Ahmadabad, Gujarat
11	Oriyo Timbo and Babar Kot	Saurashtra region, Gujarat
12	Shikarpur and Surkotada	Kutch District, Gujarat
13	Kanmer	Kutch District, Gujarat

* Nuclear Zone of the Harappan Civilization:

Harappa, Mohen-jo-Daro, Chanu-Daro and Pirak. However, the five major urban centers of the Harappan Civilization are Harappa, Mohen-jo-Daro, Ganeriwala, Dholavira and Rakhigarhi.

** The Harappan Civilization moved east and northeast and having come upon the now extinct stretch of Ghaggar-Hakra (ancient Saraswati), moved upstream and spread in the regions of Rajasthan, Punjab, Haryana and western Uttar Pradesh (Dikshit, 1980; Sharma, 1982).

*** Other important sites of the Southern region are Khirsara, Rangpur and Kuntasi, as well as some hinterland of Maharashtra.

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Table 3. Major sites of the Harappan Civilization (after Pokharia and Srivastava, 2013; Pokharia et al., 2014).

well before the decline of the Harappan Civilization (Clift et al., 2012; Singh et al., 2017).

Quaternary climate scientists emphasize the impact of weakened Summer Monsoons of South Asia at ~4.2 cal. kyr BP, leading to reduced water availability in the region and subsequent population migration to other areas (Figure 3) (Enzel et al., 1999). Various high-resolution paleoclimatic studies have demonstrated the role of climate in the evolution of the Harappan Civilization, highlighting the variability of the Summer

Monsoons of South Asia in and around the region over the last two decades (Enzel et al., 1999; Leipe et al., 2014; Prasad et al., 2014). Furthermore, Berkelhammer et al. (2012) and Dixit et al. (2014) suggested a sudden decrease in the strength of the Summer Monsoons of South Asia ~4200–4000 cal yr BP, leading to an arid phase lasting for two centuries and resulting in reduced discharge of the Indus River. However, Fontes et al. (1996) proposed that no significant climatic variability occurred during the period of 4200–4000

cal yr BP in the Western Himalaya, except for the Tso Kar Lake region, which controlled the hydrological budget of the Harappan settlements (Demske et al., 2009; Wünnemann et al., 2010; Mishra et al., 2015a). Additionally, Possehl (1997), Madella and Fuller (2006), and MacDonald (2011) also raised doubts about the displacement and deurbanization of such a widespread culture, based on a relatively short arid phase of 200 years, which is even shorter than the Little Ice Age (LIA).

Reduced precipitation during weak Summer Monsoons of South Asia led to decreased snow deposition in the Western Himalaya. This, in turn, resulted in lower water discharge from the Indus River and its tributaries, leading to reduced frequency and intensity of floods in the Indus plains (Giosan et al., 2012). Such climatic conditions could have had negative impacts on agriculture in the Indus Valley region (Giosan et al., 2012). The Indus is the central artery of the Harappan culture, as well as the primary artery for trade and commerce during peak Harappan cultural florescence. As a matter of fact, the Indus, one of the great rivers of Asia, originates in the Himalayas and flows at present through a vast dry zone before emptying into the Arabian Sea. Its fertile floodplains have sustained populations in this region for millennia. At its upper reaches the Indus system consists of the Indus and five other rivers, the Jhelum, the Chenab, the Ravi, the Beas and the Sutlej. These drainages converge near the modern city of Multan forming the trunk stream of the Lower Indus. The Ghaggar-Hakra, one of the two major river systems where the highest density of Harappan population settled, is to the east on the border between Pakistan and India. Though the Ghaggar-Hakra was once dynamic, it ceased to supply water to this region at some time in the past (Wright et al., 2008). Giosan et al. (2012) suggested that fluvial landscapes in Harappan territory became remarkably stable during the Late Holocene, as aridification intensified in the Indo-Gangetic Plain after ~5000 BP. Upstream on the alluvial plain, the large Himalayan rivers in Punjab stopped incising, whereas downstream, sedimentation slowed on the distinctive mega-fluvial ridge, which

the Indus built in Sindh. This fluvial quiescence suggests a gradual decrease in flood intensity that probably stimulated intensive agriculture initially and encouraged urbanization ~4500 BP. However, further decline in monsoon precipitation led to conditions adverse to both inundation- and rain-based farming. Moreover, it was also suggested that only Monsoon-fed rivers were active along the Harappan heartland during the Holocene unlike earlier assumptions that a large glacier-fed Himalayan river, identified by some with the mythical Saraswati, watered the Harappan heartland. As the monsoon weakened, monsoonal rivers gradually dried or became seasonal, affecting habitability along their courses. Hydroclimatic stress increased the variability of agricultural production supporting Harappan urbanism, leading to settlement downsizing, diversification of crops, and a drastic increase in settlements in the moister monsoon regions of upper Punjab, Haryana, and Uttar Pradesh.

Around 4200-3900 years ago, the population started migrating towards the Ghaggar-Hakra region and later to the Ganga-Yamuna interfluve region (Possehl et al., 1997; Giosan et al., 2012). Consequently, the Late Harappan period sites are concentrated near the Ganga and Yamuna river systems. Changes in the architectural patterns of the Harappan Civilization also indicate a decrease in rainfall in the region. Therefore, the weakening of the Summer Monsoons of South Asia likely played a significant role in the southeast displacement of the people from the Harappan Civilization and its subsequent transformation into a village culture (Dutt et al., 2019).

The primary means of subsistence for the people of the Harappan Civilization was agriculture and farming, animal husbandry, and trade activities. The main crops cultivated included wheat, barley, millets, peas, lentils, and cotton, whereas evidence of rice cultivation has also been documented (Possehl, 2002; McIntosh, 2007; Vahia and Yadav, 2011). Madella and Fuller (2006) proposed that winter precipitation served as a vital source of irrigation water, whereas Wright et al. (2008) and Giosan et al. (2012) suggested that agriculture relied less on precipitation and more on farming practices based on receding river floods. Dave

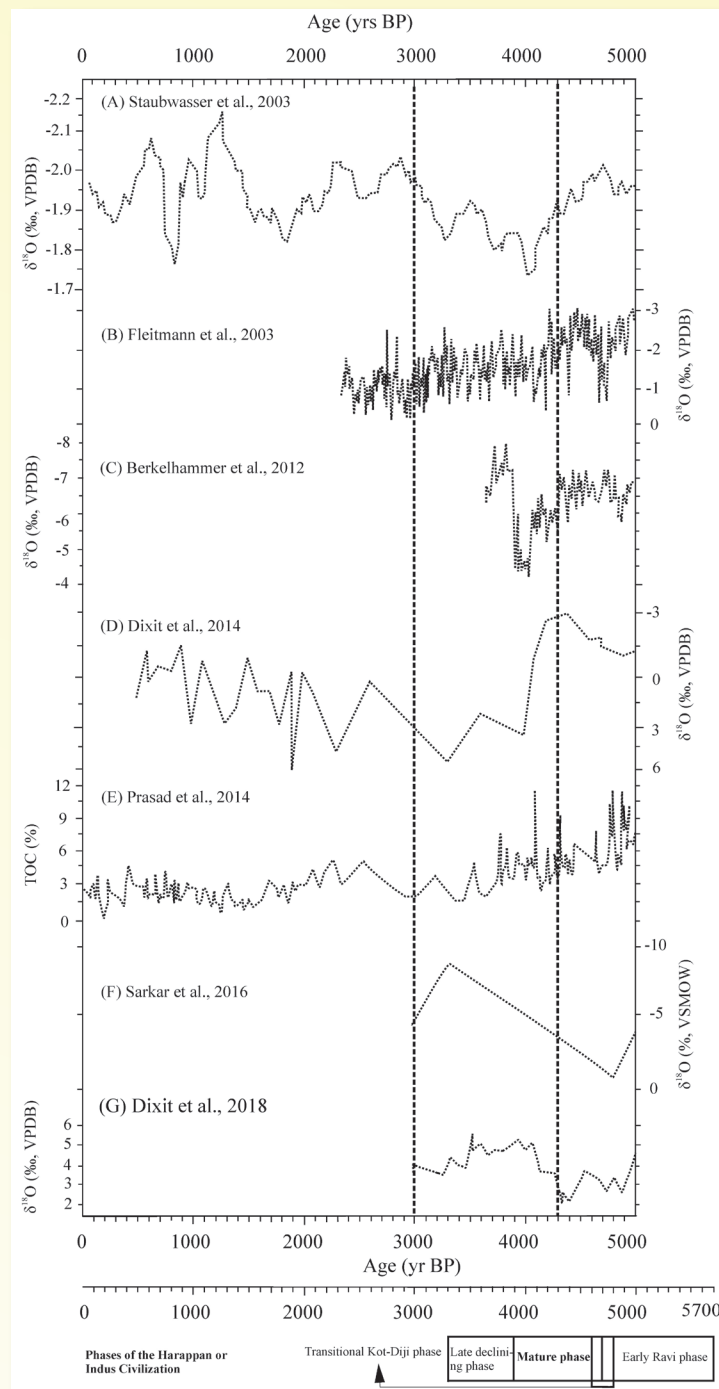


Figure 3. The weak ISM at 4.2 ka (“4.2 ka event”), recorded from (A) Hole 63 KA, Arabian Sea (Staubwasser et al., 2003), (B) Qunf cave, Oman (Fleitmann et al., 2003), (C) Mawmluh cave, Mizoram, Northeast India (Berkelhammer et al., 2012), (D) Kotla Dahar Palaeolake, Haryana, India (Dixit et al., 2014), (E) Lonar Lake, Maharashtra, Central India (Prasad et al., 2014), (F) Bhirrana archaeological site, Fatehabad District, Haryana, India, (G) Karsandi Palaeolake, Thar Desert, Nohar-Bharda District, Rajasthan, India (Dixit et al., 2018). This 4.2 ka event is believed to have caused the displacement/migration and/or decline of the IVC. The various phases of the IVC are: (1) Early Ravi Phase: ~5.7–4.8 kyr BP, (2) Transitional Kot-Diji phase: ~4.8–4.6 kyr BP, (3) Mature phase: 4.6–3.9 kyr BP, and (4) Late declining (painted Grey Ware) phase: 3.9–3.3 kyr BP (Kenoyer, 1998; Wright et al., 2008; Dikshit and Mani, 2012).

et al. (2018), drawing from their study on the smaller Harappan settlements in Haryana, suggested that water availability for irrigation and other needs likely relied on precipitation from the Summer Monsoons of South Asia. The favorable climate and high agricultural productivity during the Harappan Civilization era can be attributed to the growth of the human population. Additionally, the establishment of permanent settlements was driven by the safety and ease of food availability within communities (McIntosh, 2007). In contrast to other ancient civilizations, the Harappan Civilization did not extensively develop canal irrigation systems (Possehl, 2002; McIntosh, 2007). The surplus agricultural production, increasing population demands, and rising living standards prompted regional and foreign trade activities (Vahia and Yadav, 2011). Consequently, trade centers, such as Mohenjo-Daro and Harappa were established and connected with surrounding urban and rural settlements (Possehl, 2002; McIntosh, 2007; Vahia and Yadav, 2011). The Harappan Civilization also established trade relations with contemporary civilizations, such as Mesopotamia, Oman, and Egypt, utilizing both land and sea routes (Possehl, 2002; McIntosh, 2007). The urban settlements of the Harappan Civilization exhibited highly developed architecture, featuring houses constructed from baked bricks, a gridded street pattern, underground sewage systems, and large buildings and tanks for public ceremonies (Possehl, 2002; Vahia and Yadav, 2011). Harappa and Mohenjo-Daro were strategically established on elevated platforms, likely as a precautionary measure against regular river floods (Rao, 1991; McIntosh, 2007). These sites, along with Banawali, a Mature Harappan phase site located near the course of the Ghaggar-Hakra river system in Haryana, were surrounded by defensive walls made of bricks, further suggesting the need for protection from river floods (Rao, 1991; McIntosh, 2007). Such features indicate the frequent occurrence of floods and the abundant availability of water in these areas. The inland port at Lothal stands as evidence of the advanced engineering and technological prowess of the Harappan Civilization society (Gaur and Vora, 1999; McIntosh, 2007). Nigam et al. (2016)

proposed that the people of the Harappan Civilization were conscious about tsunamis, and the thick wall at Dholavira, Gujarat, was constructed as a defense against the high risk of tsunamis or sea storms.

CRITICAL EVALUATION OF THE ‘CLIMATE-CULTURE’ HYPOTHESIS

Ibn Khaldun (after CE 1377), an Islamic historian, first identified the challenging concept of the rise and fall of civilizations, and its attentive issues, and identified the periodic rise and fall of dynasties as macrostructures in the history of sedentary civilizations (Khaldun, 1962; Butzer, 2012). The investigation into societal collapse has fascinated the attention of scholars across disciplines, such as archaeology, history, Quaternary climate science, and others for over a century, sparking significant interest (Possehl, 2002; Staubwasser et al., 2003; Fleitmann et al., 2003, 2009; Gupta et al., 2003; Berkelhammer et al., 2012; Butzer, 2012; Pokharia et al., 2014, 2017; Leipe et al., 2014; Sarkar et al., 2016; Kotlia et al., 2017; Dixit et al., 2014, 2018; Dutt et al., 2018; Sengupta et al., 2019; Kathayat et al., 2017, 2018, 2022; Jahan and Quamar, 2024, and references cited therein). Numerous hypotheses, such as foreign invasion, social instability, decline in trade, drying of Ghaggar-Hakra system, climate change (climate deterioration), human induced environmental degradation, and change in subsistence strategy by shifting crop pattern, have been proposed to comprehend this complex issue of massive social disturbance, societal collapse, and population collapse, as well as the rise and fall of civilizations, though (Possehl, 2002; Staubwasser et al., 2003; Berkelhammer et al., 2012; Butzer, 2012; Pokharia et al., 2014, 2017; Dixit et al., 2014, 2018; Sarkar et al., 2016; Kathayat et al., 2017, 2018, 2022; Jahan and Quamar, 2024 and references cited therein). For instance, the abrupt climate change at 4.2 ka (the ‘4.2 ka drought event’) has linked with the collapse of numerous ancient civilizations, including Akkadian Empire in Mesopotamia (Riehl et al., 2013), Harappan Culture or Indus Valley Civilization (Staubwasser et al., 2003; Berkelhammer et al., 2012; Dixit et al.,

2014; Kathayat et al., 2017, 2018, 2022), the Yangtze River Valley Civilization in the lower Yangtze region of China (Wu and Liu, 2004; Yasuda et al., 2004; Liu and Feng, 2012; Zhang et al., 2021), the Longshan culture in the Huaihe River Basin of eastern China (Zhang et al., 2010), the Neolithic cultures in China's Central Plain (Wu and Liu, 2004), the broader collapse of six out of seven Chinese cultures of that era (Liu and Feng, 2012), the Mongol Empire (Pederson et al., 2014), Uyghur Empire (Di Cosmo et al., 2018), Chinese Dynasties (Zhang et al., 2008, 2015), Japanese social systems (Kajita et al., 2020), the Tibetan Empire (Chen et al., 2023), the Old Kingdom in Egypt, Egypt's Nile Valley (Stanley et al., 2003; Kennett et al., 2012), as well as Early Bronze Age civilization of Greece and Crete (Weiss and Bradley, 2000; Weiss et al., 1993; Wiener, 2014; Ruan et al., 2016). These cultures and civilizations had established and flourished during periods of more favorable climates (Cullen et al., 2000; Yasuda et al., 2004; Buckley et al., 2010; Liu and Feng, 2012; Hou et al., 2016; Dixit et al., 2018). Moreover, absence of plausible reasons behind every hypothesis has been an apple of discord among archaeologists, historians, Quaternary climate scientists, and others for over a century.

The transition from the Medieval Climate Anomaly (MCA: CE 750-1200) into the Little Ice Age (LIA: CE 1550-1850) is associated with the decline of the Khmer Empire in Cambodia (Buckley et al., 2010). The Maya Civilization developed around 3,000 years ago in Mesoamerica, and after flourishing during the so-called Terminal Classic Period (TPC) (ca. 800 to 1000 CE; drought condition), it collapsed around 750–900 AD (CE), and climate change played a part in this collapse (Hodell et al., 1995). They further asserted that the interval between 1300 and 1100 yr BP (800–1000 CE) was the driest of the Middle and Late Holocene Epoch, and coincided with the collapse of the Classic Maya Civilization. de Menocal (2001), however, suggested that the Classic Maya Empire (Maya Civilization) in Mesoamerica collapsed at the peak of their cultural development between ca. 750 and 950 AD (CE). Evans et al. (2018) also suggested that the demise of Lowland Classic Maya civilization

during the TCP is a well-cited example of how past climate have affected ancient societies.

In contrast to the abrupt and drastic weakening of the ISM strength at 4.2 kyr BP, there is evidence, suggesting a gradual decline in the monsoon from 7 to 2 ka, yet the settlements persisted (Sarkar et al., 2016). Sarkar et al. (2016) pointed out that the lack of continuous climate records close to or from the Harappan settlements presents a significant gap in our understanding of the fall of the Harappan Civilization (Bhirrana is located ~100 km south of Indus city site of Farmana). They proposed that factors, such as change in subsistence strategy through shifting crop patterns, rather than solely climate change contributed to the collapse of the Harappan Civilization. Dixit et al. (2014) also indicated that the connection between the climate event at 4.2 ka and cultural transformations in South Asia is uncertain, partly because existing palaeoclimate records originate from areas outside the distribution of Indus settlements (Kotla Dahar palaeolake is ~160 km southeast of the Indus city site of Rakhigarhi). Moreover, Bird et al. (2014) suggested that maximum ISM rainfall occurred between 10.1 and ~5.2 ka, whereas after ~5.2 ka, the ISM tended toward drier conditions to the present. Dixit et al. (2018) were of the opinion that the monsoon rainfall intensified between 5 and 4.4 ka, and drier conditions set in sometimes after 4.4 ka and by 3.9 ka. Ghosh et al. (2020) suggested that the Early Holocene was characterized by a wet phase at ca. 9 ka with 25% higher rainfall compared to present, whereas the Middle-Late-Holocene was relatively arid.

Sarkar et al. (2016) suggested that the flourishing Harappan Civilization and its decline have been linked to the intensification of monsoon during the Mid-Holocene climate optimum and its subsequent weakening, respectively. And the evidence comes from a variety of source, such as distant lake sediments in the Thar desert (Singh et al., 1974; Enzel et al., 1999, foraminiferal oxygen isotopes in Arabian sea cores (Staubwasser et al., 2002), fluvial morphodynamics (Giosan et al., 2012), and climate models (Wright et al., 2008). Although the collapse of the Harappan Culture (as well as several contemporary civilizations, such as

Akkadian (Mesopotamia), Minoan (Crete), Yangtze (China) has been attributed to either weakening of monsoon or pan-Asian aridification (drought events) at ~4.1 ka (Dixit et al., 2014; Singh et al., 1974; Enzel et al., 1999), the evidence is both contradictory and incomplete. Either the climatic events and cultural levels are asynchronous (Enzel et al., 1999; Schuldenrein 2002; Mac Donald, 2011), or the climate change events themselves are regionally diachronous (Madella and Fuller, 2006 and references therein). Moreover, Enzel et al. (1999) studied lake Lunkaransar sediment chemistry (lake Lunkaransar is located ~120 km southwest of Karsandi in the arid zone [200-250 mm/year rainfall] of the Thar Desert) and concluded that relatively dry conditions prevailed during the period of Indus urbanism, challenging the so called 'culture-climate' hypothesis (Singh et al., 1990), which purports that Indus urbanism developed under wetter climatic conditions (Dixit et al., 2018).

Dixit et al. (2014), based on $\delta^{18}\text{O}_a$ of the aragonite gastropod *Melanoides tuberculata* preserved in stratified lake sediment of Kotla Dahar palaeolake in Mewat District of Haryana State, India, suggested that the Kotla Dahar record alone cannot fully explain the role of climate change in the cultural evolution of the Harappan Civilization, and the impact of the abrupt climate event in India and West Asia records, and that observed at Kotla Dahar, on settled life in the Indus region warrants further investigation. The Indus settlements spanned a diverse range of environmental and ecological zones (Wright, 2010; Petrie, 2013), therefore, correlation of evidence for climate change and the decline of Indus urbanism requires a comprehensive assessment of the relationship between settlement and climate across a substantial areas (Weiss and Bradley, 2001; Petrie, 2013). Sarkar et al. (2016), based on $\delta^{18}\text{O}$ composition of fossil bone or tooth enamel bioapatite (carbonated hydroxyapatite) from Bhirrana (Fatehabad District of Haryana State), India, suggested that the climate data and chronology of Bhirrana suggest that the Harappan Civilization not only originated, but also flourished in the face of overall declining rainfall throughout the Middle to Late Holocene (Enzel et al., 1999; Weiss

and Bradley, 2001). It is, therefore, difficult to point to one single cause that drove the Harappan decline, although diverse suggestions from Aryan invasion, to catastrophic flood or droughts, change in monsoon and river dynamics, sea-levels, trade decline (Shaffer and Leichtenstein, 1989; Lahiri, 2000; Weiss and Bradley, 2001; Possehl 2002; Thompson et al., 2002; Ratnagar, 2006; McIntosh 2007; Giosan et al., 2012; Clift et al., 2012) to increased societal violence and spread of infectious diseases (Robbins Schug et al., 2013) have been proposed. Therefore, establishing direct correlations between climate and cultural changes is challenging. The assumption that human societies flourished during favorable climatic periods (warm and humid climate with increased monsoonal rainfall) and experienced hardship or collapse during unfavorable periods (cold and dry climate with decreased monsoonal rainfall) is not universally valid (Le Roy Ladurie, 1971; De Vrie, 1980; Wigley et al., 1981; Crumley, 1994; McIntosh et al., 2000; Tainter, 2000; Crumley et al., 2001; de Menocal, 2001; Redman et al., 2004; Hardesty, 2007; McGovern, 2007; Rosen, 2007). In many cases, cultural responses to climate resulted in increased organizational complexity and larger population sizes, even in the face of harsher environmental conditions compared to earlier periods for certain subsistence activities.

Cullen et al. (2000), Staubwasser and Wiess (2006) and Magny et al. (2013) also emphasized that the considerable uncertainty regarding the societal impact of such an event (a catastrophic desiccation ca. 4200 yr BP; the 4.2 ka event) largely due to the fact that climatic evidence often comes from regions far from the distribution of ancient settlements (Ruan et al., 2016). Butzer (2012) additionally proposed that collapse is typically multi-causal (multifaceted) and seldom abrupt. While war or climate perturbations may have acted as triggering mechanisms, (but) environmental degradation does not consistently emerge as a universal factor (Butzer, 2012). Scroxton et al. (2020) suggested that while the causes of societal decline and transitions are undoubtedly multifaceted and complex, the role of climate in the end of the Mature Phase of the Harappan Civilization warrants further study.

They propose that the 4.2 ka event may have had a more localized geographical impact than commonly assumed. Additionally, Butler (2007) and Salehyan (2008) argue that the notion of climate-induced human crisis overlooks historical complexities or relies on weak evidence of causality, leading to criticisms stemming from incomplete knowledge of the subject in question. Berkelhammer et al. (2012) and Dixit et al. (2014) suggested a sudden decrease in the strength of the ISM ca. 4200–4000 cal yr BP, resulting in a two-century-long arid phase and reduced discharge of the Indus River. However, Fontes et al. (1996) proposed that no significant climatic variability occurred during the period of 4200–4000 cal yr BP in the Western Himalaya, except for the Tso Kar Lake region, which controlled the hydrological budget of the Harappan settlements (Demske et al., 2009; Wünnemann et al., 2010; Mishra et al., 2015). Moreover, Possehl (1997), Madella and Fuller (2006), and MacDonald (2011) expressed doubts about the displacement and deurbanization of such a widespread culture, based on a relatively short arid phase of 200 years, which is even shorter than the Little Ice Age. The archaeological record suggests that the people of the Indus Valley successfully managed the pressures of climate change, migration, and rapid population growth for centuries prior to 2000 BCE. Climate change and trade relationships may have facilitated immigration to the city of Harappa after 2200 BCE. At Harappa, forces, such as urbanization, social stratification, hydro-ecological stress, agro-economic issues, disruptions in trade networks, and deteriorating conditions likely contributed to the collapse. By 1900 BCE, massive depopulation occurred, with remaining inhabitants facing increased rates of interpersonal violence (Lovell, 1989; Kennedy, 1976, 1982, 1984, 1992, 2000, 2002; Sharma, 1999), and infection (Robbins Schug et al., 2009, 2013), particularly in marginalized communities with little protection from a weak, decentralized society. While climate change presents a significant challenge for human communities, it alone does not dictate the fate of human societies; it is one variable intertwined with political, social, historical, and

cultural forces (Judkins et al., 2006; Costanza et al., 2007; Rosen, 2007; Adger et al., 2009; Brooks et al., 2009; Wossink, 2009; McAnany and Yoffee, 2010). Bryson (1981), Wright (1993), Enzel et al. (1999), Von Rod (1999), Singh and Bengtsson (2004), Madella and Fuller (2006) and Migowski et al. (2006) also suggested that the Harappan Civilization evolved in the context of a semi-arid climate prevalent in South Asia for the latter half of the Holocene.

Therefore, some archaeologists have opposed and critiqued the notion of linking the ‘4.2 ka drought event’ with the simultaneous decline of the Harappan Civilization, citing two primary reasons (Gupta et al., 2003; Madella and Fuller, 2006; Pakharia et al., 2017). First, there is evidence suggesting long-term aridification throughout the Holocene, implying that the Mature phase of the Harappan Civilization may have emerged in response to water scarcity rather than abundant rainfall (Gupta et al., 2003; Madella and Fuller, 2006). Second, there are indications of adaptation and continuity within the Mature Phase of the Harappan Civilization despite drying (Pakharia et al., 2017). Hence, several gaps persist in the understanding of the hypothesis proposing climate-driven collapse of the Harappan Civilization. Firstly, the evidence for aridification in the Indian subcontinent does not consistently align with a sudden 300-year long drought followed by a return wetter conditions, as might be expected if the 4.2 ka event were the sole cause (Madella and Fuller, 2006; Wright et al., 2008). Secondly, the most plausible climate mechanism for changes in the ISM, involving a shift in El Niño-Southern Oscillation (ENSO) state and increased El Niño frequency, occurred 300 years later than the proposed timing (MacDonald, 2011).

EPILOGUE

Climate change has had an important influence on the migrations, and collapse of the Harappan Civilization. Climate deterioration at ~4.2 ka is known as one of the drivers of the fall of the Harappan Civilization. The 4.2 ka event and the simultaneous

fall of the Harappan Civilization has sparked extensive debate and disagreement among various disciplines, such as archaeology, Quaternary climate science, meteorology, climatology, history, geography, and archaeobotany and other disciplines. The abrupt climate change at the 4.2 ka is cited as the most plausible reason for the fall of the Harappan Civilization, rather than the socio-economic and political turmoil. Probably a combined influence of the weakened Summer Monsoons in South Asia and reduced glacial discharge from the Himalayas due to colder condition caused decline and forceful migrations of the settlers of the Harappan Civilization. In fact, less precipitation and snowmelt (from the Himalaya), in turn, reduced the discharge of Indus River and its tributaries, and, subsequently, the frequency and intensity of floods in the Indus plains, affecting the agricultural productivity, and, ultimately the societal resilience (Staubwasser et al., 2003; Giosan et al., 2012). Thus, a weakening of the Summer Monsoons in South Asia might have played a major role in southeast displacement of the people of

the Harappan Civilization and its transformation into a village culture later (Dutt et al., 2019).

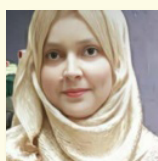
Different schools of thought, however, exist on this inordinately fascinated, and much debated issue. However, it seems reasonable that rather than one specific cause, the compounding of the many in a feedback loop could, in fact, explain better the supposed “fall” of the Harappan Civilization.

The study provides critical background for current environmental impact, especially in regions prone to droughts. Moreover, the study offers valuable lessons for scholars, policymakers, politicians, and for the general public to develop scientifically informed strategies that address societal needs effectively.

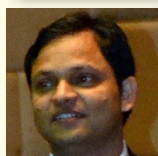
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About authors



Dr Tarannum Jahan earned her Ph.D. degree in History from Babasaheb Bhimrao Ambedkar Bihar University, Muzaffarpur, India. She is working as a Teacher of History at Azad Academy, Araria District, Bihar.



Dr Mohammad Firoze Quamar is Senior Scientist at BSIP, Lucknow. His research interests mainly include the reconstruction of ISM-driven vegetation dynamics and contemporary climate change during the late Quaternary in the CMZ of India, as well as in the Himalaya, Western Ghats and Western India. He also takes keen interest in studying Non-Pollen Palynomorphs (NPPs), especially the Spores of Coprophilous Fungi (SCF), as well as in aerobiology and melissopalynology.

A Lake That Remembers 25,000 Years of Indian Monsoon History from Bakhira Lake

Nazakat Ali and Biswajeet Thakur

THE quiet waters of Bakhira Lake in eastern Uttar Pradesh may seem far removed from the great climatic changes that shaped the Indian subcontinent during the Late Quaternary. Yet beneath its surface lies a remarkable archive of environmental history. Layer after layer of sediment has accumulated in the lake over thousands of years, quietly preserving evidence of changing rainfall, river activity, weathering, geochemical evidences and landscape conditions.

A recent study of these sediments has revealed a continuous record extending back about 25,000 years. The record captures some of the most important climatic episodes of the Late Quaternary, from the Last Glacial Maximum to the present day, and shows that the Indian Summer Monsoon (ISM) has never been a completely stable system. Instead, it has repeatedly strengthened and weakened in response to changes occurring both within the Indian region and far beyond it.

Lake sediments

A lake is more than a body of water. It can also act as a natural sediment trap. Every year, rivers, streams, wind and surface runoff carry particles from the surrounding landscape into a lake. During periods of stronger rainfall and runoff, larger and greater quantities of sediment may reach the basin. During drier conditions, sediment transport may become weaker and finer particles may dominate. Scientists can, therefore, examine these layers much like pages in a history book. But instead of words, the pages contain minerals, grains and chemical elements.

At Bakhira Lake, researchers recovered a sediment sequence about four metres long and analysed hundreds of samples at closely spaced intervals (Figure 1). Supported by seven accelerator mass spectrometry radiocarbon dates provided the chronological framework, indicating that the sequence preserves approximately the last 25.3 thousand years.

The age model also shows that sediment accumulated at different rates through time, with an average temporal resolution of roughly 124 years for each 2-cm interval. Several independent clues were then combined. Grain size helped reveal changes in the energy of sediment transport. Clay minerals provided information about whether the source region experienced stronger physical erosion or more intense chemical weathering. Major and trace elements supplied additional evidence about weathering and sediment provenance. The strength of the reconstruction comes from the fact that these different lines of evidence tell a broadly consistent story.

The oldest part of the Bakhira Lake sequence, extending from about 25.3 to 18.1 thousand years ago, records relatively weak hydrological activity. Fine-grained sediment dominates, while the coarse sediment component is relatively limited. Chemical weathering indicators are also comparatively low. Together, these characteristics point towards reduced runoff, weaker river activity and limited chemical alteration of rocks in the source region. This interval broadly overlaps with the Last Glacial Maximum (LGM), when large ice sheets covered extensive areas of the Northern Hemisphere and global temperatures were considerably lower than today. The Indian Summer Monsoon was also weaker during this period. In the

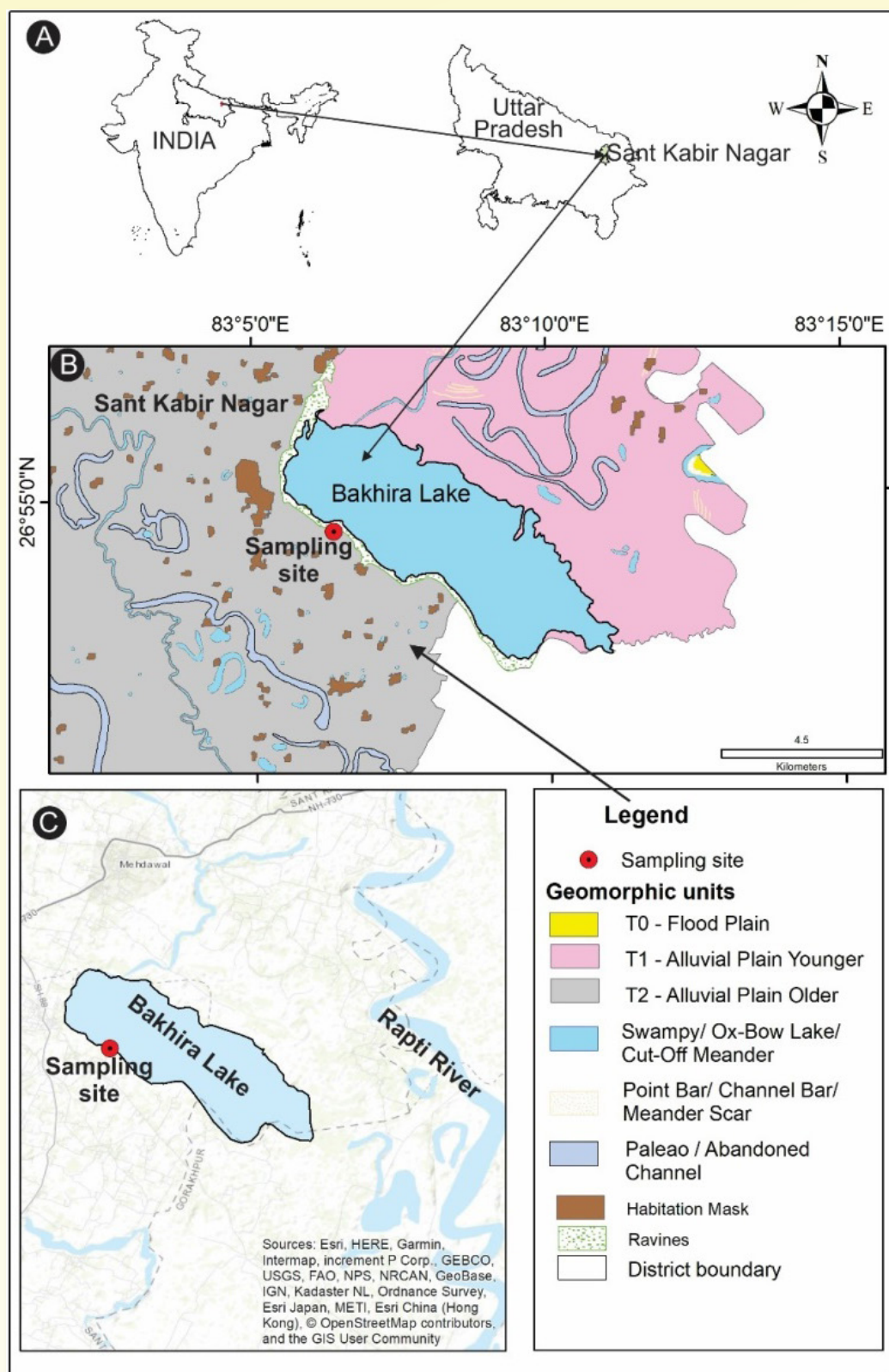


Figure 1. Location and geomorphological setting of Bakhira Lake, showing the study site, major geomorphic units, surrounding palaeochannels and wetlands, and its relationship with the Rapti River and local drainage network.

Central Ganga Plain, such a weakening would have affected not only rainfall but also the movement of sediment through rivers and floodplains. The Bakhira Lake sediments, therefore, preserve more than a record of rainfall: they also capture how the landscape responded to a changing climate.

After the LGM, the climate began to change rapidly. Between approximately 18.1 and 16.8 thousand years ago, the Bakhira record shows an increase in coarser sediment and stronger indicators of chemical weathering. These changes suggest greater runoff and stronger fluvial activity under warmer and wetter conditions. This interval represents one of the periods when the ISM strengthened markedly. But the recovery was not smooth. Around 16.8–15.3 thousand years ago, the record again shows finer sediments and weaker weathering signals.

This interval broadly corresponds to Heinrich Stadial 1, a period of pronounced climatic deterioration associated with changes in the North Atlantic climate system. The weakening of the Indian monsoon during this interval demonstrates something important: the monsoon does not respond only to conditions over India. Climate disturbances in distant parts of the Earth can influence the circulation system that delivers rainfall to South Asia. The climate then shifted again. From roughly 15.3 to 12.85 thousand years ago, coarser sediment became more prominent and chemical weathering intensified.

These signals are consistent with stronger runoff and a strengthened monsoon during the Bølling–Allerød, a relatively warm interval during the final stages of the last deglaciation. The story changed once more with the Younger Dryas. Between approximately 12.85 and 11.08 thousand years ago, finer sediments, reduced coarse sediment input and weaker weathering indicators point towards another period of weakened monsoon activity.

The sequence of warming, strengthening, weakening and renewed strengthening shows that the monsoon system can change rapidly rather than simply moving in one direction.

The beginning of the Holocene brought another major transformation. Between approximately 9 and

4 thousand years ago, the Bakhira sediments indicate stronger fluvial activity and enhanced chemical weathering.

This interval coincides broadly with the Holocene Climate Optimum, when many regions experienced warmer and wetter conditions than during the preceding millennia. The monsoon was stronger, but even this apparently favourable period was not uniform. The lake record shows fluctuations within the broader strengthened phase, reminding us that monsoon variability occurs at several timescales.

Then came another major change. Between about 4 and 2 thousand years ago, the sediments became finer and chemical weathering weakened. These changes indicate a reduction in rainfall and runoff. The interval corresponds broadly with the widely recognised 4.2 ka aridity event, which has been identified in several South Asian palaeoclimate records. After approximately 2 thousand years ago, the Bakhira record suggests renewed strengthening of monsoonal rainfall. Thus, over the Holocene alone, the lake records a strong monsoon, a pronounced weakening and a subsequent recovery.

The Bakhira record raises a larger question: why does the monsoon change? One important control appears to be the amount of summer sunlight received by the Northern Hemisphere. Over thousands of years, Earth's orbit changes gradually, altering the seasonal distribution of solar energy. The Bakhira reconstruction shows broad agreement between long-term changes in monsoon strength and Northern Hemisphere summer insolation.

But orbital changes alone cannot explain every rapid shift. Events, such as Heinrich Stadial 1 and the Younger Dryas occurred much more quickly than orbital changes. These abrupt events are linked to major reorganisations of the climate system, including changes in the Atlantic Meridional Overturning Circulation (AMOC). Changes in high-latitude climate can influence atmospheric circulation, the position of the Intertropical Convergence Zone and the transport of moisture towards South Asia. The Bakhira record, therefore, provides an important reminder that the Indian monsoon is connected to the

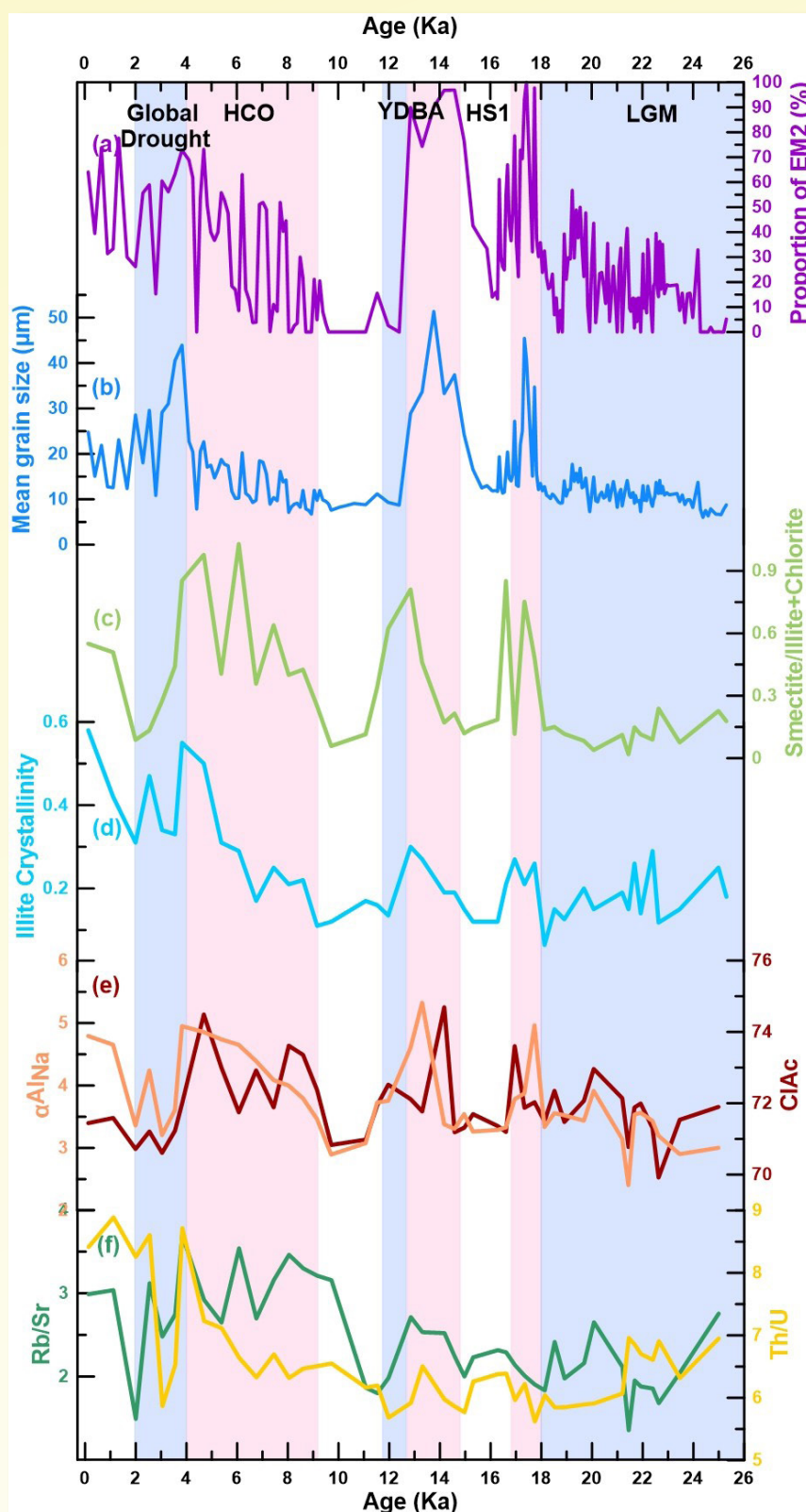


Figure 2. Variations in sediment grain size, clay mineral composition and geochemical weathering indicators in the Bakhira Lake sediments.

wider Earth system. A change thousands of kilometres away can eventually be reflected in the sediments of a lake in the Ganga Plain.

The value of palaeoclimate research is not simply to reconstruct what happened in the distant past. It is to understand how the climate system behaves when conditions change. Modern observations of rainfall extend over only a relatively short period compared with geological timescales.

The Bakhira Lake record provides a much longer perspective. It demonstrates that the ISM has experienced repeated episodes of strengthening and weakening, sometimes over relatively short intervals. This long-term perspective is particularly important for India. The monsoon supports agriculture, groundwater recharge, river systems, wetlands and millions of livelihoods. Understanding its natural range

of variability can help us place present-day changes in a broader context. The sediments beneath Bakhira Lake, therefore, represent much more than mud deposited on the lake floor. They preserve a record of changing rivers, landscapes, weathering and rainfall, and, ultimately, of a monsoon system that has repeatedly responded to a changing Earth.

The lake has been silent for thousands of years. Its sediments, however, have been telling the story all along.

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About authors



Mr Nazakat Ali is pursuing Ph.D. from BSIP, Lucknow. His research focuses on Indian Summer Monsoon variability using multi proxy approach, including grain-size studies, clay mineralogy, geochemistry, palynofacies analysis, and environmental magnetism.



Dr Biswajeet Thakur is currently serving as Scientist 'F' at the BSIP, Lucknow. His research focuses on multi-proxy approaches to investigate past climate variability across diverse geographical settings, particularly the western and eastern coastal margins of India.

From tree rings to apple orchards: unravelling short-term climate extremes in the western Himalaya

Ravi S. Maurya and Krishna G. Misra

IN recent decades, changes in weather and climate have become an increasing threat to agriculture, particularly in mountainous regions where farming systems depend heavily on natural climatic conditions. Variations in rainfall, temperature, snowfall, and water availability can influence crop growth, productivity, and the timing of important agricultural activities. Short-term weather events, including droughts, floods, heatwaves, hailstorms, and intense rainfall, can cause considerable damage when they occur during sensitive stages of crop development. At the same time, long-term climate change is altering the frequency, intensity, and timing of several of these events. Such changes can create additional challenges for farmers and increase uncertainty in agricultural production.

Agriculture in the Himalayas is particularly sensitive to climatic variability because farming communities depend heavily on seasonal rainfall, winter snowfall, and water supplied by mountain streams and springs. The timing and amount of precipitation are important for maintaining soil moisture and supporting crop growth. Rainfall that occurs too early or too late in the growing season can affect crop development, while intense rainfall over a short period can cause soil erosion, flooding, and crop damage. Similarly, prolonged dry periods can reduce soil moisture and water availability, affecting both crop growth and livestock systems. Rising temperatures, declining or irregular snowfall, prolonged dry spells, floods, and other extreme weather events are adding further pressure to mountain agriculture. For many



Figure 1. Apple phenology and fruit development in the Himalayan region: (A) apple flowering stage and (B) mature apple fruits.

rural households, agricultural production is closely connected with household income and food security, therefore, even a single season of poor crop production can have significant socioeconomic consequences.

Among the important agricultural activities in Himachal Pradesh, apple cultivation has a particularly strong connection with the climate. Apple is one of the most important fruit crops of the state and provides a major source of income for many farming communities. Himachal Pradesh is the second-largest apple-producing state in India after Jammu and Kashmir. Apple belongs to the family Rosaceae and the genus *Malus* and is mainly cultivated in the higher mountain areas of the state, generally between about 1,500 and 2,700 m above sea level. The crop has become an important component of the hill economy, supporting farmers, orchard workers, traders, transporters, and other people associated with the horticultural sector.

The development of commercial apple cultivation in Himachal Pradesh dates back more than a century. Samuel Evans Stokes Jr., an American who came to the hills of Himachal Pradesh, recognized the similarity between the region's cool mountain environment and areas in the United States where apples were successfully cultivated. In 1916, he planted *Red Delicious* apple trees at Kotgarh near Shimla. The trees

performed well under the local mountain conditions, demonstrating the potential of apple cultivation in the region. Over subsequent decades, apple orchards expanded to different parts of Himachal Pradesh and gradually became an important source of livelihood for mountain communities. The expansion of apple cultivation transformed the agricultural economy of several high-altitude areas, where the rugged terrain and short growing season often limited traditional farming. Today, apple cultivation occupies approximately 49% of the total area under fruit crops in Himachal Pradesh and supports the livelihoods and employment of many people.

Climatic conditions closely control the productivity of apple orchards throughout the annual growth cycle. Temperature, rainfall, snowfall, frost, and the timing of seasonal transitions all influence tree growth, flowering, pollination, fruit development, and final yield. During winter, apple trees require sufficient chilling to complete dormancy and prepare for normal bud development and flowering. Changes in winter temperature can, therefore, influence the fulfilment of chilling requirements and the subsequent timing of spring development. During spring, suitable temperatures are necessary for flowering and pollination. Temperatures that are unusually high or low during this sensitive period can affect flower development, pollen viability, pollination, and fruit setting. During the growing season, moderate temperatures and adequate moisture are important for healthy vegetative growth and fruit development. Temperatures around 21-24 °C are generally considered favourable for apple growth and fruit development, although the optimum conditions can vary with cultivar, altitude, and local environmental conditions.

The flowering period is one of the most climate-sensitive stages of apple production in Himachal Pradesh. Flowering generally occurs from late March to April, although the exact timing varies according to altitude, location, cultivar, and temperature. Weather conditions during this period can strongly influence the eventual harvest. Short periods of drought can reduce soil moisture and water availability when flowers and newly developing fruits require adequate



Figure 2. Hail protection nets are installed over apple orchards to protect apple trees and fruits from hailstorm damage.

moisture. Water stress may weaken flowers, interfere with pollination and fruit set, and ultimately result in fewer, smaller fruits. Hailstorms pose another major risk during this period. Hail can physically damage flowers, leaves, and young fruits, leading to flower and fruit drop and reducing fruit quality. Severe hailstorms may also break branches and cause structural damage to trees, affecting production beyond the immediate growing season. Consequently, drought and hailstorms occurring during the flowering period can result in substantial reductions in yield, fruit quality, and farmers' income.

The sensitivity of apple cultivation to climate highlights the importance of understanding both long-term climate variability and short-lived weather

events. Apple trees require a relatively narrow balance of temperature and moisture throughout their annual growth cycle. Changes in rainfall patterns, snowfall, temperature, and the timing of seasonal transitions can disturb this balance. Increasing climatic variability may also expose orchards to weather conditions that differ substantially from those experienced during the establishment of traditional apple-growing systems. Understanding how the climate has varied in the past can, therefore, provide useful information for evaluating the vulnerability of mountain agriculture and identifying periods when climatic conditions were particularly favourable or unfavourable for agricultural production.

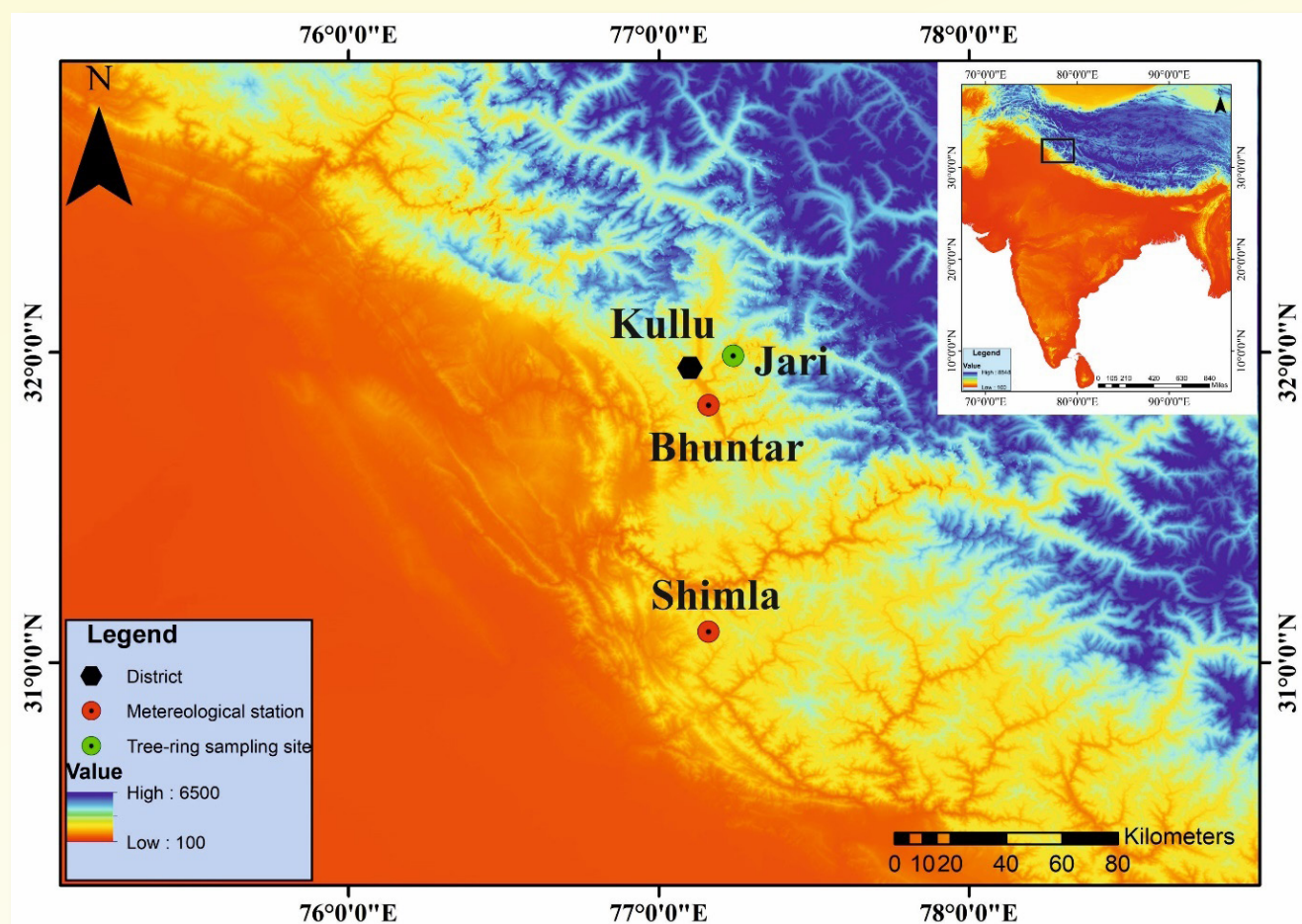


Figure 3. Map showing the tree-ring sampling location and the meteorological station used in the present study.



Figure 4. Images showing the intra-annual density fluctuations (IADFs): **(A)** IADF in earlywood, **(B)** IADFs in latewood, **(C)** two successive IADFs in earlywood, **(D)** IADFs in both early and latewood.

Long-term climate information is especially valuable in the Himalayas because instrumental observations are relatively limited in many high-altitude, remote areas. Meteorological observations generally cover only the recent part of the climate record, whereas many environmental and agricultural questions require information extending over several centuries. Tree rings provide an important means of extending the climate record beyond the period covered by instrumental observations. Because trees respond to environmental conditions during their growth, their annual rings can preserve information about past variations in temperature, moisture, and drought. Tree-ring records have, therefore, been widely used to investigate long-term climate variability and environmental changes in mountainous regions.

The value of tree rings for climate studies is particularly relevant to agriculture. Long-term tree-ring records can reveal periods of unusually dry or wet conditions and help place recent climatic events within a much longer historical context. Such records can improve understanding of the occurrence and persistence of droughts and wet periods and provide information about the natural range of climate variability. This historical perspective is useful for climate-sensitive agricultural systems, including apple cultivation and crops, such as wheat and barley. However, conventional tree-ring measurements generally provide information at annual to seasonal scales and may not clearly identify short-duration climatic events that occur during the growing season. A drought lasting only a few weeks or a brief period

of unusually heavy rainfall may have a strong effect on tree growth, but may not be clearly separated when the entire annual ring is considered as a single unit.

The Himalayan cedar (*Cedrus deodara*) is a long-lived coniferous species native to the Himalayan region and represents an important natural archive for investigating past environmental conditions. Its natural distribution extends from Afghanistan through the western Himalayas, including the Garhwal and Kumaun regions. The species commonly grows on steep and rocky slopes with well-drained soils and is frequently associated with areas receiving moderate to heavy winter snowfall. It generally occurs between 1,200 and 3,300 m above sea level, although its distribution varies with local environmental conditions. Its broad geographical distribution, long lifespan, and sensitivity to climatic conditions make Himalayan cedar particularly useful for dendrochronological investigations.

A forest near Jari in the Parvati Valley of Kullu, Himachal Pradesh, was selected to examine the relationship between climate and Himalayan cedar growth. The study area has a complex geological setting and includes rocks, such as phyllite, quartz schist, and limestone. In May 2022, 30 core samples were collected from 25 Himalayan cedar trees. The samples were processed and examined to develop a 214-year tree-ring chronology spanning 1808 to 2021. This long chronology provides an opportunity to investigate variations in tree growth over more than two centuries and to examine the climatic conditions associated with changes in growth patterns.

An important aspect of the study is the identification of intra-annual density fluctuations (IADFs) within the tree rings. IADFs are distinct bands or changes in wood density that develop within an annual ring during the growing season. Their formation is generally associated with temporary changes in environmental conditions that interrupt or modify the normal pattern of wood formation. Changes in rainfall and temperature during different stages of the growing season can influence cambial activity and the production of earlywood and latewood, resulting in visible density variations within

the annual ring. Unlike the conventional interpretation of a tree ring as a single annual record, the position of an IADF within the ring can provide information about when a particular climatic disturbance occurred.

The intra-ring position of IADFs is, therefore, particularly useful for identifying short-term climatic events. An IADF occurring near the beginning of the growing season may preserve evidence of a brief dry period or early-season drought that temporarily affected tree growth. In contrast, an IADF occurring toward the later part of the growing season may be associated with a short period of exceptionally high rainfall or a pluvial phase. Thus, the location of an IADF within an annual ring provides an additional seasonal dimension to dendrochronological records. Intra-annual density fluctuations in earlywood (IADFe) feature thick-walled tracheids with narrow lumens, which are flanked on both sides by the wide, thin-walled tracheids characteristic of normal earlywood. This specific structural variation is triggered by a soil moisture deficit during the initial phases of the growing season. Conversely, latewood fluctuations (IADF_l) present as large, thin-walled tracheids embedded within the typically dense latewood zone. This phenomenon is driven by a sudden surge in available soil moisture during the latter part of the growing period. This information is important because two years with similar annual rainfall totals may have experienced very different rainfall distributions. One year may have received adequate rainfall throughout the growing season, whereas another may have experienced an early-season drought followed by intense late-season rainfall. Annual ring width alone may not adequately distinguish these contrasting seasonal conditions, whereas IADFs can preserve evidence of such short-term changes.

The analysis of IADFs in Himalayan cedar, therefore, provides a more detailed perspective on climate variability than annual growth measurements alone. By examining the occurrence, frequency, and position of IADFs and comparing them with instrumental climate records, it is possible to identify climatic conditions associated with their formation. In particular, early-growing-season IADFs can

indicate short-duration drought conditions, while late-growing-season IADFs can indicate brief periods of unusually high rainfall or pluvial conditions. Such signals are important for understanding the seasonal nature of hydroclimatic variability in the Himalayan region.

Overall, IADF analysis strengthens the use of Himalayan cedar as a high-resolution proxy for past climate variability. It enables short-lived climatic events during the growing season to be distinguished from broader annual climate conditions and provides information on the timing and occurrence of hydroclimatic extremes. This seasonal information is especially relevant to Himalayan agriculture, where the timing of rainfall and dry conditions can be as

important as the total amount received. By revealing evidence of short-term droughts and pluvial episodes preserved within annual tree rings, IADFs provide a valuable link between dendrochronological records and the climatic events that influence mountain ecosystems and climate-sensitive agricultural systems.

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About authors



Dr Ravi S. Maurya is a Research Associate at the BSIP, Lucknow, working on an ANRF-sponsored project. His research focuses on palaeoclimate reconstruction in the western Himalaya using tree-ring records, with interests in hydroclimatology, climate variability, and glacier-climate interactions.



Dr K G Misra is a Dendrochronologist and works as a Scientist 'E' at the BSIP, Lucknow. His research interests mainly include hydroclimate reconstructions, natural hazards, high-altitude ecology with crop production, and glacier dynamics in the Himalayan region during the Late Holocene.

Dzukou Valley, Nagaland: A Paradise under Climate Change and Anthropogenic Pressure

Sandhya Misra

DZUKOU Valley, often described as the “Valley of Flowers” of Northeast India, lies high in the mountains of Nagaland, along the border with Manipur. The valley (Latitude: 25°31’0” N to 25°35’0” N; Longitude: 94°03’0” E to 94°05’0” E), located at an altitude of 2450m and 30 km south of Kohima, is known for its scenic beauty and holds environmental significance due to its unique and rich biodiversity. The serene beauty of the valley and the surrounding landscape attains its peak after the monsoon. The lush green hills covered with dwarf bamboo look like a rolling grassland from a distance, with mist-covered ridges, zigzag seasonal streams, dwarf bamboo meadows, and colourful endemic and wild flowers, especially the endemic lily, all coming together to give the valley a spectacular view (Figure 1).

The valley holds significant importance in the Naga socio-cultural history and is inhabited by the local tribal population of Ao, Angami, Sumi, Lotha, and Chakhesang tribes. They consider the valley sacred, venerate it, and play a pivotal role in its conservation. Over the past few decades, the valley’s popularity has spread beyond the northeast and reached far-off places. It has now become one of the most celebrated natural and trekking destinations in northeast India. With the growing human population in surrounding areas and footfall in the valley, the fragile ecosystem behind this breathtaking scenery is at stake. Human intervention, repeated forest fires, increasing tourist pressure, careless human activities, waste generation, and the growing push for tourism infrastructure have severely stressed the valley’s floral biodiversity, resulting in changes in vegetation composition and, consequently, landscape change.

For many visitors, Dzukou may be a beautiful tourist/trekking destination. But it’s not; indeed, its significance is much greater than it seems from external views. It is a natural laboratory for understanding mountain ecology, climate variability, vegetation change and the relationship between fire and biodiversity. Its forests and grasslands provide habitats for wildlife, while its vegetation contributes to soil stability, water regulation and carbon storage. For researchers, Dzukou offers an opportunity to understand how high-elevation ecosystems respond to natural and human disturbances. For local communities, it represents an important cultural and natural heritage.

FLORISTIC UNIQUENESS OF DZUKOU VALLEY

Dzukou is not just a beautiful tourist destination; the widespread combination of high-elevation grasslands, dwarf-bamboo vegetation, forest patches, streams, and surrounding mountain slopes and valleys offers habitats for a wide variety of plants and animals. It has attracted botanists and taxonomists over time to explore its rich floral diversity. The floristic uniqueness of the valley can be understood from the fact that 01 genus represents 50 families, 01 species represents 128 genera, and Annonaceae, Illiciaceae, Magnoliaceae, Ranunculaceae, and Schisandraceae represent 19 primitive angiosperm species (5%). Floral diversity is significant at regional and global scales. This is demonstrated by plant diversity, which exhibits a close affinity with neighbouring countries, such as Tibet, China, Bhutan, and Nepal.



Figure 1. 1 & 2 View of Rest House at the Dzukou Valley; 3 & 4 View of surrounding forest and Bamboo covered hills in heart of Dzukou.

Ecologically, the landscape is not simply a collection of individual species but an interconnected network of plants, animals, soil, water, forests, grasslands, and mountain ecosystems. Hence, an alteration in one component can directly influence other components of this fragile ecosystem.

THREATS TO THE BIODIVERSITY OF DZUKOU VALLEY

Repeated Wildfires: An Ecological Threat

The recurring fire regime in the Dzukou Valley and adjoining hills has become a serious threat, negatively impacting not only the floral wealth, but also leading to changes in species composition, vegetation structure,

flowering season of *Rhododendron* and *Prunus* species found in valley and tree line shift to higher elevations. Forest fires are a part of natural ecosystem in several parts across the globe. But in context to Dzukou valley, frequent fire recorded especially during the winter/dry season, March-May seems not be a part of natural ecosystem. The published records show that these fire episodes increased in frequency and extent, especially over the past two decades, due to ease in trekking from easily approachable tracks. Looking into the extent and the damage fire caused, years 2006, 2010, 2012, and 2015 identified as devastating fire years. In the current scenario, smaller fires have become an annual feature of the valley. The recent fire, i.e., the 2026 event, was very substantial, with significant burning across southern, eastern, and western areas and adjoining mountain

ranges. Thus, based on field experiences from 2015 to 2025 and interactions with local researchers and older folks, it was found that following every fire incident, the endemic dwarf bamboo species colonises new areas and suppresses the existing native and endemic vegetation of the valley, thereby negatively impacting their regeneration or growth. This is clearly reflected in the Quadrant studies conducted in the valley: the number of species in each quadrant decreased, and *Sinarundianaria rollana* (dwarf bamboo) showed dominance. This clearly indicates that these fire episodes were neither simple nor temporary. Frequent occurrence and wide extent altered the ecological character of the valley over time and across space.

2. Human intervention: a threat beyond fire

Forest fires are only one part of the problem; the most threatening issue is the rise in human intervention, which is yet another major issue that needs to be addressed to protect and conserve this ecologically sensitive and fragile ecosystem.

During the field survey and interaction with the old folks of native tribes involved with the care and management of the valley, researchers in local colleges and universities, and other literary sources, it is found that during the early 70's, white elephants used to visit the valley, the valley had much more variety of flowers than what we see today, the path to valley was much difficult. A decline in the flora can also be understood by the fact that the flora administered in old literature, even in the last and latest extensive botanical survey conducted two decades ago, and the extant vegetation in the valley and surrounding hill region has changed a lot over time and space, attributed to the natural state of climate change with limited or intermittent human interference. Regarding the limited human interventions, according to oral sources gathered through interactions with locals, their ancestors tried to grow crops and vegetables in the valley. Still, the cold and harsh conditions of the valley are not conducive to human colonisation or settlement. Since then, the trial has been ongoing: during the 2015 field survey, it was noted that the caretakers at the valley's rest house

were trying to grow ginger and garlic in the backyard of the rest house and tourist cottages, and even during the 2024 visit, the situation was the same.

Taking into account the 2024 field survey, published literary sources, social media posts, travel bloggers and tourism packages it was noticed that the popularity of the remotely located pristine Dzukou valley has crossed its boundaries and fascinated trekkers and tourists from far and wide, resulting in an increase in the number of footfalls each day and a rise in number of visitors in the tourism season negatively impacting the pristine environment of Dzukou. It is undeniable that increased tourism provides livelihoods for locals, but one cannot overlook the adverse impact of unmanaged tourism, which is severely altering the place's serenity.

This increasing number of trekkers is leading to the trampling of endemic vegetation, disturbance of wildlife, littering, collection of flowers and other plants, soil erosion and the gradual development of informal trails. The Key Biodiversity Areas database specifically identifies increasing tourism, non-degradable solid waste (Figure 2), and the collection of the endemic Dzukou lily as threats to biodiversity in the area.

3. Climate change: a natural resilience to biodiversity

Climate change over a long period of time and space impacts not only the immediate environment, but also impacts its constituent elements, resulting in alteration in the edaphic condition (soil properties), sensitivity to external forcing (fire, landslide, rainfall, etc.), reflected in changes in vegetation composition and forest structure over time.

In the context of Dzukou, multi-proxy investigations covering the last ~11000 years documented changes in vegetation as reflected in changes in carbon isotope, magnetic susceptibility, and even pollen/spore data. It was found that the vegetation response was in coherence with the changing global climate data. The proxy data also recorded the impacts of global climatic events. In these studies, it was also noted that the frequency of fire incidents increased

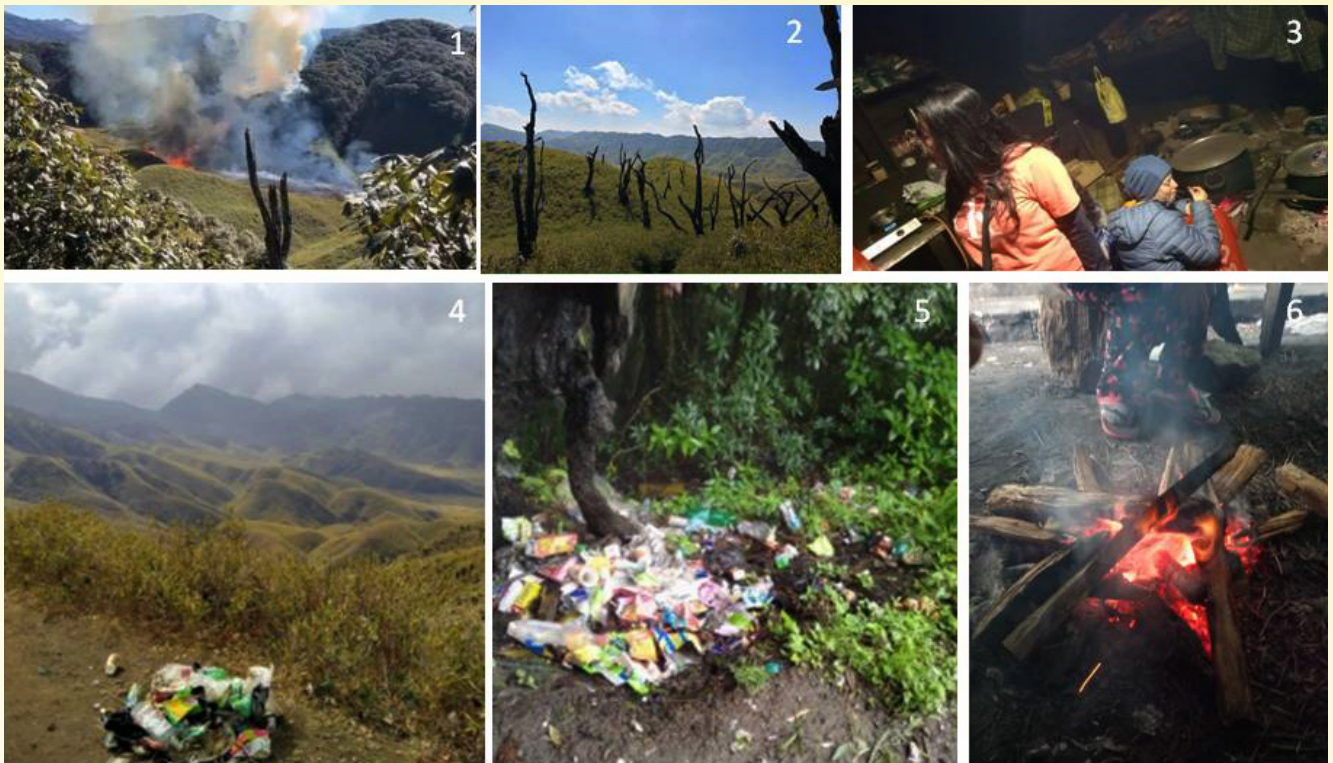


Figure 2. 1. A view of fire in Dzukou valley; 2. Burnt stumps of *Juniperus* trees on slopes of valley; 3 & 6 Fire activity in the rest house and tourist cottages at rest house; 4 & 5 Non biodegradable waste by visitors in the valley.

after 1500 years BP, attributed to both natural climate drivers and increased human population in adjoining areas, as well as the expansion of dwarf bamboo.

SUSTAINABLE SERENE DZUKOU: LESSONS AND LEARNING

Based on scientific evidence of climate change recorded in multi-proxy studies from Dzukou and the author's personal field observations over the past decade, it is evident that the valley's floristic diversity was resilient to natural climate change until the last 1500 years. For a long time, Nagas were hunter-gatherers across various regions. Still, in due course of time, realising the need for a settled life, they started colonising the adjoining parts, viz., the western part of Khonoma village ~700 years ago, and Viswema in the southern part is considered centuries old. Initial interventions by the settled population included exploring adjoining areas for hunting animals/birds, identifying suitable areas for agriculture, and

collecting food, fruits, and fuelwood. Until 2015, the state retained its natural climate, and human interference was not that devastating; food and good accommodations were also issues for a vegetarian. But over a decade, during the 2024 field excursion, the scenario completely changed. The single narrow roads turned into a six-lane highway; narrow mud streets with thickets of vegetation all along and zig zag paths leading to remote areas turned into clean motor able roads, concrete buildings replaced lush green forests; several homestays resolved the struggle for accommodation; goods from neighbouring borders dominated markets; and the search for a local guide to the valley ended with a large number of travel agencies.

PREVENTION BEFORE PROTECTION

In view of the facts and figures, field observations, and scientific findings, it is realized that what was/is put at stake is worth more than what we gained in the name of development and urbanization. Wide roads

and increasing concrete are opening the door to a wide range of problems, limiting and diminishing the green face of the state. The 2026 fire incident in Dzukou, caused by human error, is an alarming call to take action to prevent excessive human interference. We need to look for remedial measures for such incidents in the future by establishing fire-watch towers, fire lines, rapid-response teams, drones, firefighting equipment, and early-warning systems, and, most importantly, legally controlled visitors.

While looking for measures to protect the valley, we find the locals to be the best choice. They are not only ecologically connected to Dzukou, but also have their socio-cultural faith in this natural treasure. While working in different parts of the state, it was interesting to know that what we researchers find ecologically or economically important has one or the other folklore associated with it. This indicates that the local beliefs and folklore associated with various places are actually

an indigenous method of conserving and protecting these sites, which can be explained and documented with substantial scientific investigations. In line with this, community-conserved landscapes in Nagaland demonstrate that local stewardship can make a significant contribution to biodiversity conservation.

It's high time that the local conservation organizations, village councils, youth groups, forest authorities, researchers, and tourism operators worked together to formulate and establish a legal framework for the comprehensive Dzukou conservation programme. A future in which local communities become the primary custodians of the landscape; visitors become conservation partners; scientific research guides management; tourism generates sustainable livelihoods; and fire prevention becomes a shared responsibility.

The message is, therefore, simple: Let's live, learn and love Dzukou by leaving Dzukou alive.

About author



Dr Sandhya Misra, a DST Women Scientist at the BSIP, Lucknow, investigates interactions between natural climate variability and human activities that shape vegetation and landscape dynamics. She integrates palynology and archaeobotany to reconstruct past environments, trace early agro-pastoral practices, human-environment interactions, and long-term ecological changes across diversified geographical parts of India.

Did Ancient Climate Change drive Mahogany out of the Indian Forests?

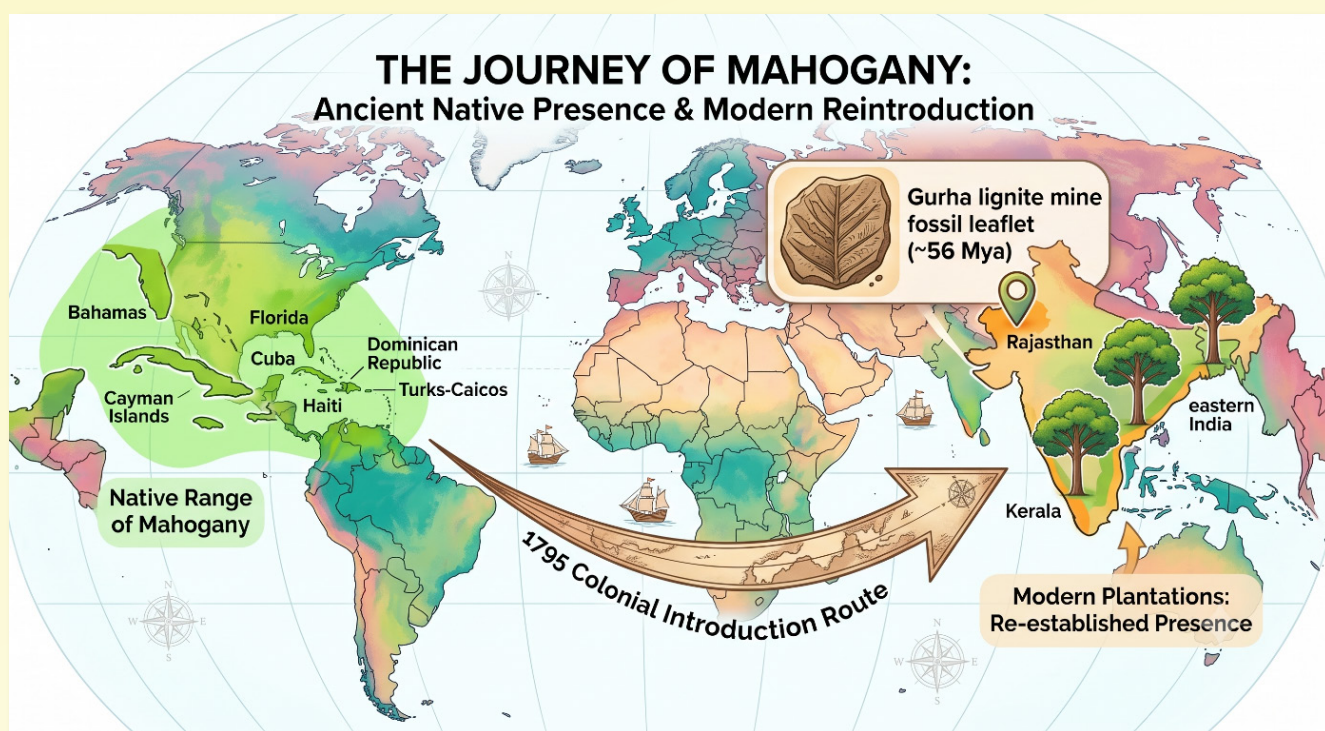
Kajal Chandra, Samiksha Shukla, Vikram Singh Thakur and Anumeha Shukla

FOR millions of years, India has preserved an extraordinary botanical record within its rocks, lignite deposits, and ancient sediments. These palaeobotanical archives contain fossil leaves, pollen, seeds, wood, fruits, and other plant remains that once formed diverse landscapes, many of which have long since disappeared. Far more than remnants of ancient life, these fossils provide valuable evidence for reconstructing the vegetation, climate, geography, and environmental changes that shaped the Indian subcontinent through geological time. By studying these plant fossils, researchers can reconstruct India's ancient landscapes and forests and trace their transformation over millions of years.

Among the many stories preserved in these palaeobotanical archives, some challenge our assumptions about the origins and history of plants that are now familiar components of the Indian landscape. One such remarkable story is that of mahogany—a tree whose history in India is far older



(A) Mahogany fossil leaflet (B) Modern leaflet resembling the mahogany fossil.



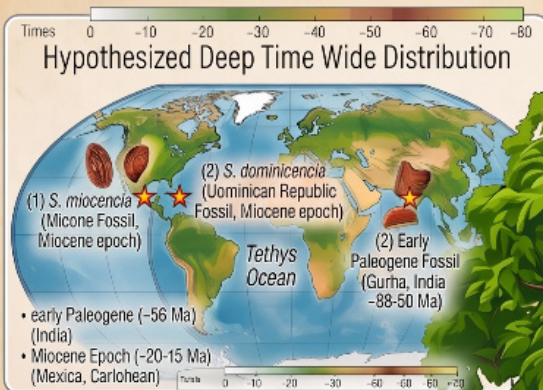
Journey of mahogany from its native region to India

and more intriguing than its present-day presence might suggest. Often revered as the “king of timber”, mahogany is highly valued worldwide for its durable wood and is extensively used in construction and furniture making. Beyond its economic importance, the tree also holds ethnobotanical significance, with various parts traditionally used in remedies for ailments, such as malaria, diabetes, and diarrhoea. Its leaves have also been used as mosquito repellents and in the preparation of soaps and herbal tonics. Mahogany was introduced to India around 1795 during the colonial period, primarily for its valuable timber. Its natural distribution is restricted to parts of the Caribbean and the Americas, including the Bahamas, Cayman Islands, Cuba, the Dominican Republic, Florida, Haiti, Jamaica, and the Turks and Caicos Islands. Thus, in the conventional account of India’s flora, mahogany is regarded as an economically important but introduced species. Today, however, mahogany has become a familiar presence across parts of the Indian landscape. From plantations in Kerala to tree-lined avenues in eastern India, its tall, straight

trunk and distinctive reddish wood may appear so well established that its introduced status is easily overlooked.

This narrative changed with the discovery of a ~56-million-year-old *Swietenia* leaflet from the Gurha lignite mine in Rajasthan, northwestern India. A well-preserved fossil leaflet, assignable to the genus that yields commercial mahogany worldwide, provides direct evidence that a members of the mahogany lineage once grew in India during the early Paleogene (~56 Mya), long before colonial introductions. This fossil evidence suggests that mahogany’s relationship with India is far older than its plantation rows and roadside avenues would suggest: a deep-time presence that vanished and was later echoed by human-mediated reintroduction. Now, the question arises: if *Swietenia* once thrived in early Paleogene India, what led to its disappearance? The answer lies in the tectonic and climatic evolution of the subcontinent. During its northward drift from the Southern Hemisphere, India passed through the various latitudes, eventually reaching its current position. During its journey, as

Paleogeography and History of the Genus *Swietenia*



A vastly wider initial range for the genus, spanning across linked landmasses documented by fossils on multiple continents.

USES OF MAHOGANY TIMBER

-  **Premium Furniture & Cabinetmaking**
(due to rich color, attractive grain, and high dimensional stability)
-  **Historical & Modern Boatbuilding**
(outstanding resistance to water and decay)
-  **Luthiery**
(Guitars, violins, and other instruments – backs, sides, and necks for superb tonal qualities)
-  **High-End Architectural Millwork**
(paneling, ornate doors, and decorative trim)
-  **Veneer & Inlay Work**
-  **Woodturning and Carving**

Modern Mahogany: Global Trade, Management, and Conservation

CONTEMPORARY GLOBAL MARKETS & CULTIVATION:

Managed plantations and sustainable practices are essential to meet high market demand.



MODERN MAHOGANY TRANSPORTATION & LOGISTICS

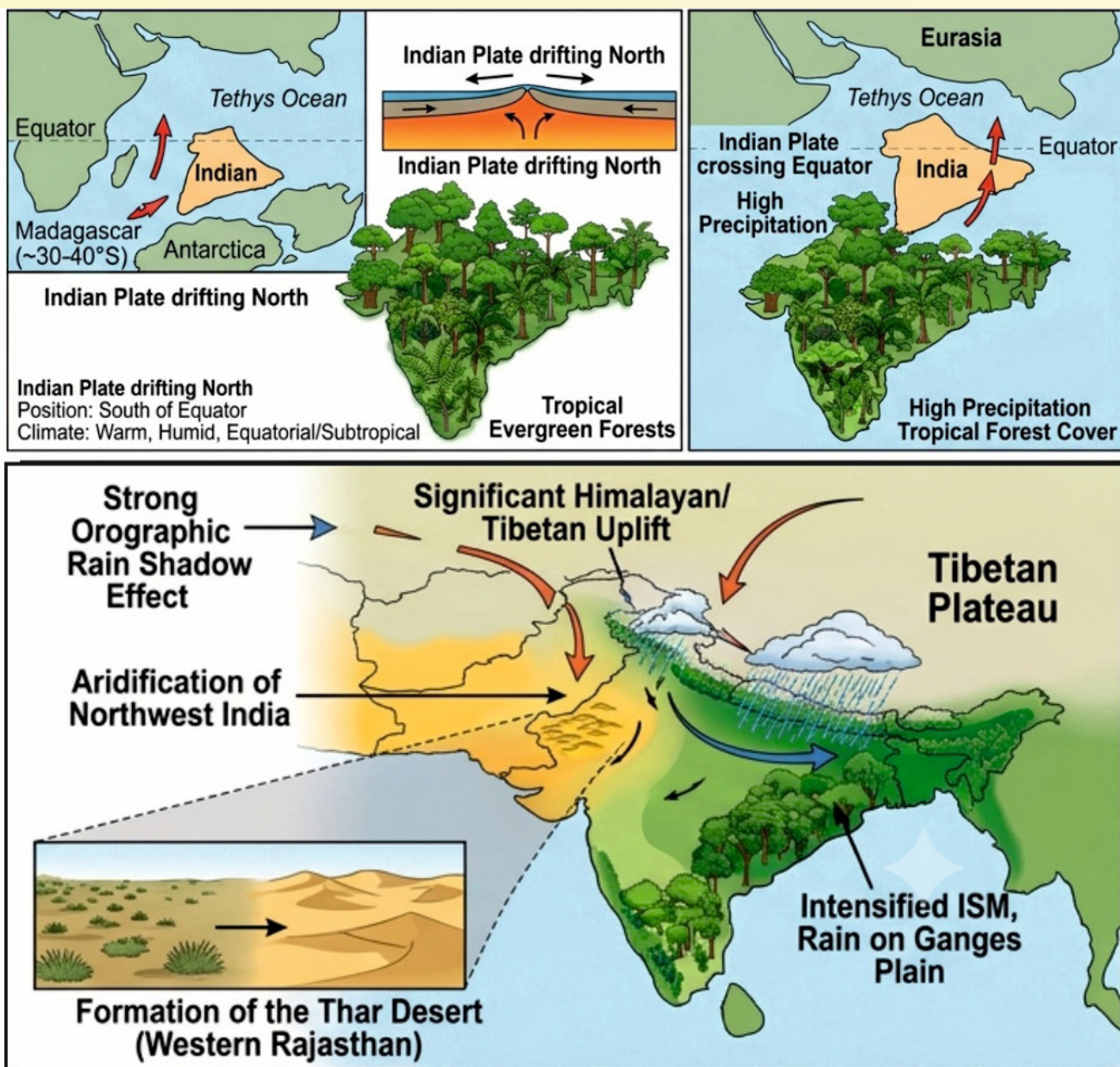
THE MAHOGANY SUPPLY CHAIN: A robust logistics network ensures efficient movement from source to international ports.



Paleobiogeography and introduction of mahogany in India.

it neared the equator, it experienced warm, humid conditions—highly favourable for the growth of tropical forests. This is also supported by the presence of fossils of several tropical plant families, including Phyllanthaceae, Annonaceae, Fabaceae, Anacardiaceae, Malvaceae, Myrtaceae, Rubiaceae, Meliaceae, and

Moraceae, recorded from the Gurha lignite mine. A previous study also indicated that the region had a mean annual temperature of $\sim 24^{\circ}\text{C} \pm 2.82^{\circ}\text{C}$, a high mean annual precipitation of ~ 1800 mm, and an annual relative humidity of approximately 80%, indicating pronounced wet–dry seasonality, consistent



Geological and climatic evolution on the Indian plate.

with an early monsoonal regime. These conditions are well known to support the diverse tropical plant communities, including *Swietenia*. Today, *Swietenia* survives only in the Neotropics, where a warm, humid climate prevails.

As the Indian subcontinent continued its northward drift and eventually collided with Eurasia,

the regional climate began to shift. The development of the monsoon system and the gradual aridification of northwestern India transformed once-humid forests into drier, more seasonal landscapes. These changing conditions likely made the environment increasingly unsuitable for *Swietenia*, contributing to its disappearance from the subcontinent. The fossil

record, thus, tells not only a story of presence but also of losses, driven by the tectonic and climatic forces that reshaped India's vegetation over millions of years.

So, the next time you pass by *Swietenia* trees planted along an Indian road or growing in a forest plantation now, you know that they are no longer merely colonial-era introductions. They also represent a botanical echo of a deep-time presence, a genus, that

once formed part of India's natural flora, disappeared as the subcontinent's climate and tectonic setting evolved, and was reintroduced millennia later through human hands. The mahogany of today is, thus, both an introduced taxon and a biogeographic homecomer, and its history is inscribed not only in timber and ethnobotanical use, but also in the fossiliferous strata of western India.

About authors



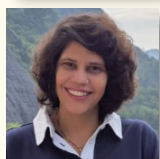
Kajal Chandra is working as a Research Associate (BSRA) at the BSIP, Lucknow. Her research focuses on elucidating the evolutionary history of angiosperms, with particular emphasis on their spatio-temporal origin, patterns of diversification, and responses to varying climatic and tectonic regimes.



Samiksha Shukla is a research scholar at the BSIP, Lucknow, and the Academy of Scientific and Innovative Research (AcSIR), India. Her research focuses on Cenozoic plant megafossils, palaeobiogeography, and palaeodiversification, employing systematic and phylogenetic approaches.



Vikram Singh Thakur is a research scholar at the Department of Botany, University of Lucknow, Lucknow, pursuing doctoral research at the BSIP, Lucknow. His research focuses on Cenozoic plant-insect interactions, their responses to climatic change, and the implications for ancient ecosystem dynamics.



Anumeha Shukla works on plant fossils to understand the evolution and diversification of angiosperms and their responses to climate change since the Cenozoic Era. Her research on early Palaeogene sequences of the Indian subcontinent provides key insights into past floristic exchanges and intercontinental palaeobiological connections.

The Mountains Remember: Are We Creating Another Lost World?

Harshita Bhatia and Gaurav Srivastava

The mountains are changing

THERE is something about mountains that makes them seem eternal. They rise above us, silent and enormous, while generations come and go below. Yet mountains are not frozen in time. Today, they are among the places where the effects of a changing climate are becoming increasingly visible. Glaciers are shrinking, snow patterns are changing, water availability is becoming less predictable, and plants and animals are being forced to adjust to a warmer and increasingly uncertain world.

For millions of people, this is far more than an environmental story. Mountains are the sources of rivers, store enormous amounts of water in the form of snow and ice, and provide homes for an extraordinary variety of plants and animals. Their steep slopes create many different environments within a relatively small area, allowing an astonishing diversity of life to exist close together. But this very diversity can also make mountain ecosystems vulnerable. As temperatures rise and rainfall patterns change, species may be forced to move higher in search of suitable conditions. For those already living near the highest slopes, there may eventually be nowhere left to go.

So, how unusual are the changes we are witnessing today? Have mountain climates changed this dramatically before? And what happened to the plants and animals when they did?

To answer these questions, we need to look beyond the mountains of today and travel deep into their past. Fortunately, the ancient landscapes have left behind remarkable witnesses. Their fossils preserve glimpses of climates, forests and ecosystems that

disappeared millions of years ago, and they tell us that the mountains we know today have not always been the same.

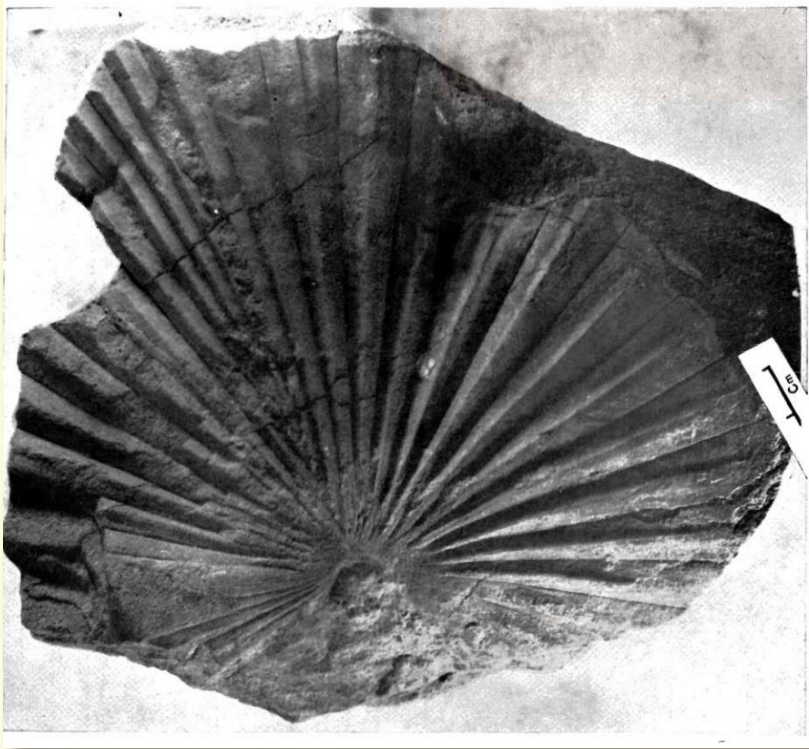
A green Ladakh?

Look at the Trans-Himalayan landscape of Ladakh today and it is difficult to imagine a forest there. The landscape is dominated by enormous barren mountains, dry valleys and scattered vegetation. Yet buried within these mountains is evidence of a very different world.

About 23 million years ago, a palm grew in what is now Ladakh. Fossil leaves of *Trachycarpus ladakhensis* were discovered near Liyan at an astonishing altitude of about 5,400 metres above sea level. Today, it is difficult to imagine a palm growing in such a cold and dry landscape. But the palm tells us something important about the climate of that lost world. Its presence suggests that the average temperature during the coldest months was at least about 5°C, and that the environment was sufficiently humid to support palm growth.

The palm was not alone. Trees related to *Broussonetia* also grew in the region, while by around 10 million years ago, trees related to *Diospyros* and *Lagerstroemia* were present as well. Together, these plant fossils paint a picture of a warm, humid and much greener Trans-Himalayan landscape than the Ladakh we know today.

Think about the contrast. A place that now appears dry and almost treeless once supported plants that we would associate with much warmer and wetter environments. Today, the region around the fossil



Fossil fan palm recovered from Ladakh (~23 Million yrs) (after Lakhanpal et al., 1984)

locality receives only about 600–650 mm of rainfall each year and has a much colder and drier climate. Somewhere between these two worlds, the climate changed, and the vegetation changed with it.

The mountains were changing too. As the Himalaya continued to rise, their influence on the movement of air and water across the region also changed. Mountains can redirect winds and influence where moisture can travel. The fossils, therefore, provide more than a record of ancient plants; they offer a glimpse into a time when the relationship between the mountains, climate and biodiversity of the Trans-Himalayan region was very different from today.

But Ladakh is only one part of the story.

The Kashmir that remembered the monsoon

Travel west, and another remarkable story emerges from Kashmir.

Beneath the beautiful Kashmir Valley lie the Karewas, ancient layers of sediment that accumulated

over millions of years. These sediments preserve fragments of landscapes that have long disappeared, including fossil leaves from plants that once grew around the valley.

The leaves preserved in the Kashmir Basin tell us that about 4 million years ago, Kashmir was warmer and much wetter than it is today. The ancient landscape received around 1,234 mm of rainfall each year, with rainfall strongly concentrated in the warmer months. The wettest month received about 221 mm, while the driest received only about 11 mm. The growing season lasted around nine to ten months, and the vegetation carried a strong signature of the summer monsoon rainfall.

The ancient air was also considerably more moisture-rich than today. The reconstructed atmospheric moisture was nearly

twice the modern value, pointing towards a much more humid environment in the past. Today, Kashmir has a very different climate, with winter precipitation brought mainly by the Western Disturbance.

This was a very different Kashmir from the one we know today.

But the most fascinating part of the story is that the mountains themselves were changing.

When the mountains changed the rain

The Pir Panjal Range was rising around the Kashmir Valley. As the mountains grew, they increasingly became a barrier to moisture-laden summer winds. The change was extremely slow, far too slow for anyone to notice within a human lifetime, but over millions of years, its effects were profound.

Evidence from the Karewa sediments suggests that the Kashmir region remained influenced by the South Asian Monsoon until around 1.95 million years ago. As the Pir Panjal Range rose, it increasingly



Fossil wood of *Lagerstroemia* L. discovered from the Ladakh (~10 Million yrs) (Srivastava et al., 2018)

restricted the entry of summer monsoon moisture into the valley, contributing to the development of the Mediterranean-type climate that characterizes Kashmir today. In other words, the mountains were not simply responding to climate. They were helping shape it.

And when the rainfall changed, the vegetation changed with it. Plants that once lived in the ancient Kashmir landscape disappeared from the region, leaving their traces behind in the sediments. The fossils, therefore, record not only a change in climate, but also a change in biodiversity.

Mountains, climate and the fate of biodiversity

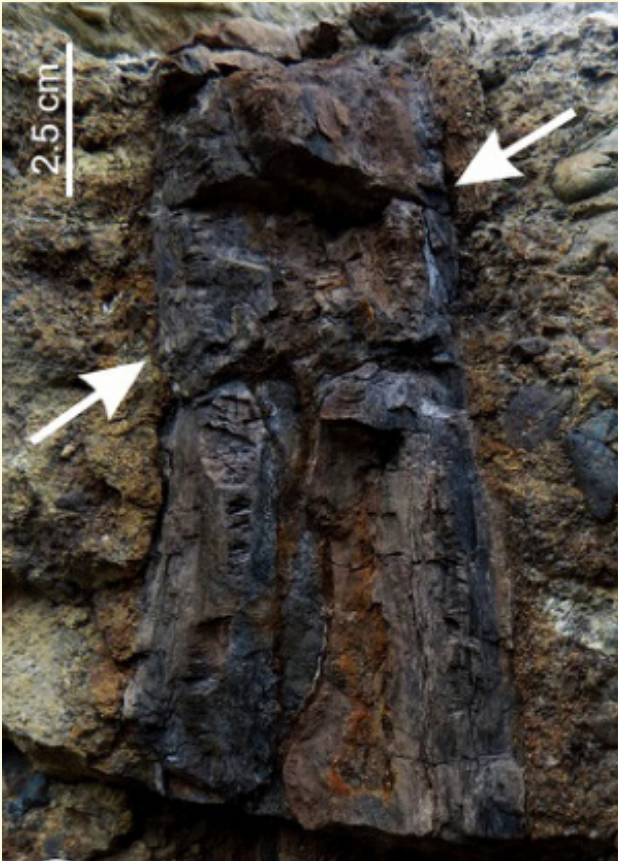
The stories of Ladakh and Kashmir reveal something fundamental: mountains, climate and biodiversity are inseparable.

Change one, and the others can respond.

A warmer climate can alter snow and ice. Changes in snow and rainfall can affect rivers and soil moisture. Changing water availability can alter forests and grasslands. As vegetation changes, animals that depend on particular plants and habitats may also be affected. Over time, an entire ecosystem can look different.

Mountain ecosystems are especially sensitive because life is arranged along narrow climatic zones. As temperatures rise, many plants and animals may move towards higher elevations. But unlike a flat landscape, a mountain has a natural boundary at its summit. A species cannot keep moving upwards forever.

This makes climate change more than a question of whether a particular species can tolerate a warmer temperature. The bigger question is whether its entire habitat can move with the changing climate.



Fossil wood of *Lagerstroemia* L. discovered from the Ladakh (~10 Million yrs) (Srivastava et al., 2018)

The fossil record shows that this has happened before. The plants of ancient Ladakh are no longer part of the landscape there today. The vegetation of ancient Kashmir also changed as the climate and rainfall regime changed. These lost landscapes remind us that biodiversity is not fixed. It is continually responding to the environment.

Are we creating another lost mountain world?

The climate is changing again, but this time the circumstances are very different.

Today's changes are occurring alongside deforestation, habitat fragmentation, intensive land use, pollution, infrastructure development and growing pressure on natural resources. Mountain ecosystems that were already naturally fragmented are now facing several pressures at the same time.

Imagine a plant growing on a mountain slope today. As temperatures rise, it may move higher to remain within the climate it can tolerate. But if its habitat becomes fragmented by roads or human settlements, its ability to move may be limited. If rainfall changes at the same time, simply moving uphill may not be enough. Its pollinators, competitors and other organisms may also need to move with it.

The result may not always be dramatic at first. A species may become less common. A forest boundary may slowly shift. A stream may begin flowing differently. A plant may disappear from one slope while surviving on another. But when many such changes occur together over decades, an entire mountain ecosystem can be transformed.

This is where the fossil record becomes especially valuable. It gives us a much longer view than modern observations alone. It shows that when mountain climates change, vegetation does not simply remain where it is. Forests expand and contract, species disappear from some regions and survive in others, and landscapes can eventually become almost unrecognizable.

What will the future mountains remember?

The fossil record cannot tell us exactly what Kashmir or Ladakh will look like a hundred years from now. Ancient climate changes occurred under



Fossil wood of *Diospyros* L. discovered from the Ladakh (~10 Million yrs) (Bhatia et al., 2022)



Fossil leaves excavated from the Kashmir Valley belonging to ~4 million years in age (after Bhatia et al., 2025)

circumstances very different from those of the modern world, so the past cannot simply be used as a blueprint for the future.

But it can give us something equally important: perspective.

It reminds us that the mountains we see today are only one moment in a much longer story. Millions of years ago, palms grew in a region that is dry today.

Ancient Kashmir experienced summer rainfall that no longer reaches the valley in the same way. Mountains rose, climates changed, and plants followed those changes.

Today, we are writing another chapter of that story.

The difference is that we can see the changes while they are happening. We can measure temperatures,

observe glaciers, monitor rivers and document changes in vegetation and biodiversity. More importantly, we can decide how we respond.

Perhaps, millions of years from now, someone will discover a fossil from our time. They may find the remains of a plant that once grew on a Himalayan slope and wonder what happened to the ecosystem around it. They may find evidence of glaciers, forests or wetlands that no longer exist.

What story will those fossils tell?

Will they record a time when mountain biodiversity was protected and allowed to adapt? Or will they record another lost mountain world?

That question is still ours to answer.

The mountains have changed before. Their fossils remember.

But this time, we know the story is being written, and we still have a chance to influence its ending.

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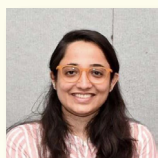
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About authors



Dr Harshita Bhatia is working as a Birbal Sahni Research Associate (BSRA) at the Cenozoic Palaeofloristics Lab., BSIP, Lucknow. Her research focuses on understanding how Indian vegetation and climate have interacted and evolved throughout the Cenozoic Era.



Dr Gaurav Srivastava is a Senior Scientist at BSIP, with expertise in paleobotany and climate evolution. His current research explores hyperthermal events and hydrological changes in South Asia from the Late Cretaceous through the Cenozoic.

When Climate changes, Forests move: What Plant Fossils from Rajasthan reveal about a warming World

Samiksha Shukla, Vikram Singh Thakur, Kajal Chandra and
Anumeha Shukla



A rainforest beneath today's arid and semi-arid region

IMAGINE travelling back millions of years to western India (Rajasthan and Gujarat). The landscape around you would be almost impossible to recognise. Instead of endless dunes, thorny shrubs, and dry, dusty plains, you might have looked across a much greener world: one with warmer temperatures, greater moisture, rivers and wetlands, and dense forests with a multilayered canopy.

Among those trees may have been *Dipterocarpus*, a member of the tropical tree family Dipterocarpaceae. Today, *Dipterocarps* are closely associated with the humid forests of South and Southeast Asia. Some members of the family are among the tallest trees in tropical forests, rising high above the

surrounding vegetation. India still supports members of this family, including Sal (*Shorea robusta*), as well as other dipterocarps distributed across humid regions from the western coast of Karnataka to the southern tip of the

Indian Peninsula and northeastern India.

But the present-day distribution of plants tells only part of their story. Fossils show that plants have not always lived where they do today. As

temperature, rainfall and seasonality change, plant ranges can expand, shift, become isolated, or disappear. The fossils of *Dipterocarpus* from western India are a striking example. Today, the region is largely arid and semi-arid, making a humid-forest tree like *Dipterocarpus* seem completely out of place. Its fossil record reveals a bigger story: when climate changes, the map of plant life changes too.

MILLIONS OF YEARS AGO, HUMID TROPICAL FORESTS COVERED PARTS OF WESTERN INDIA. THEIR TRANSFORMATION INTO TODAY'S ARID LANDSCAPES REVEALS HOW POWERFULLY CLIMATE CAN RESHAPE THE DISTRIBUTION OF PLANT LIFE.

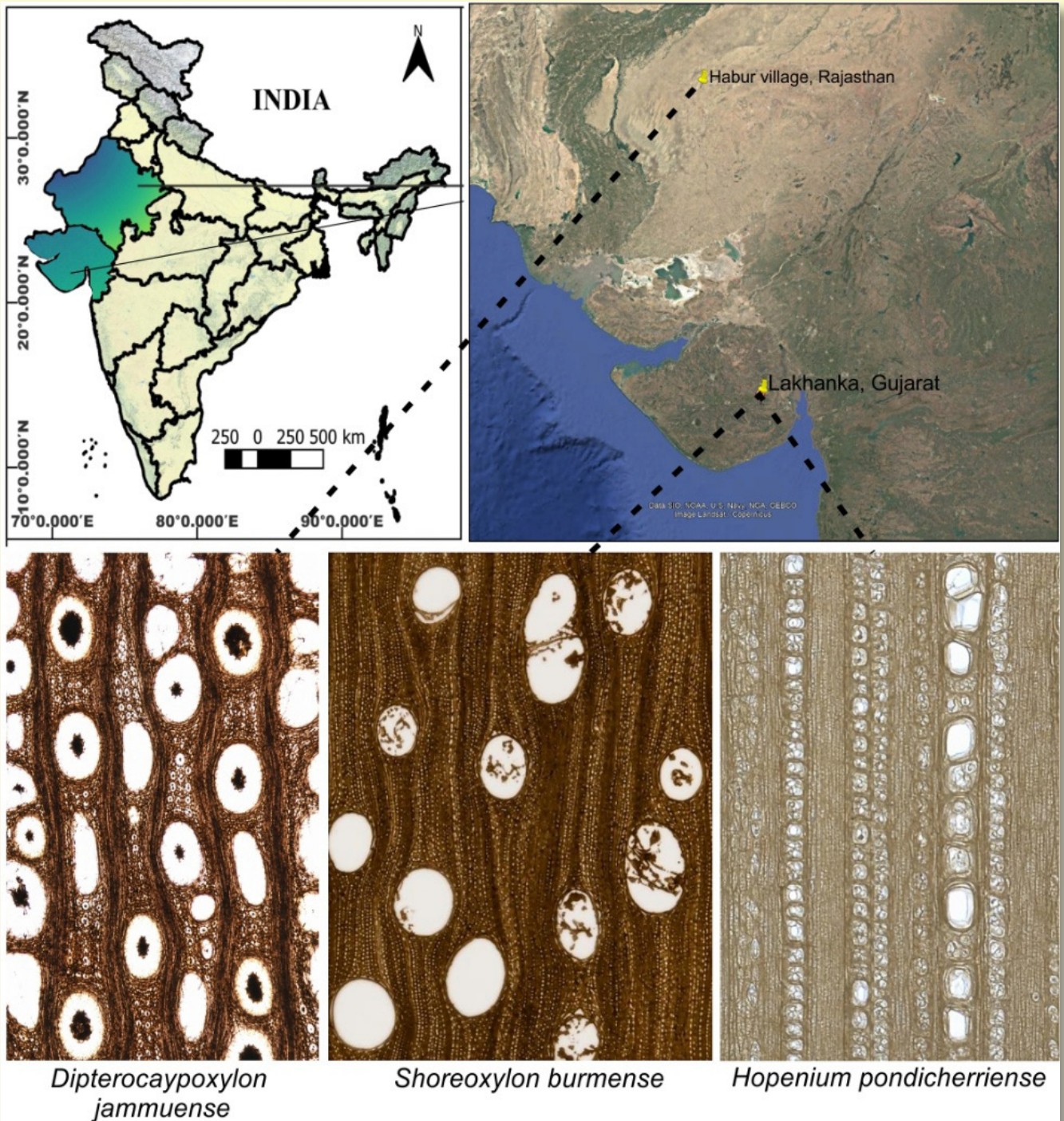
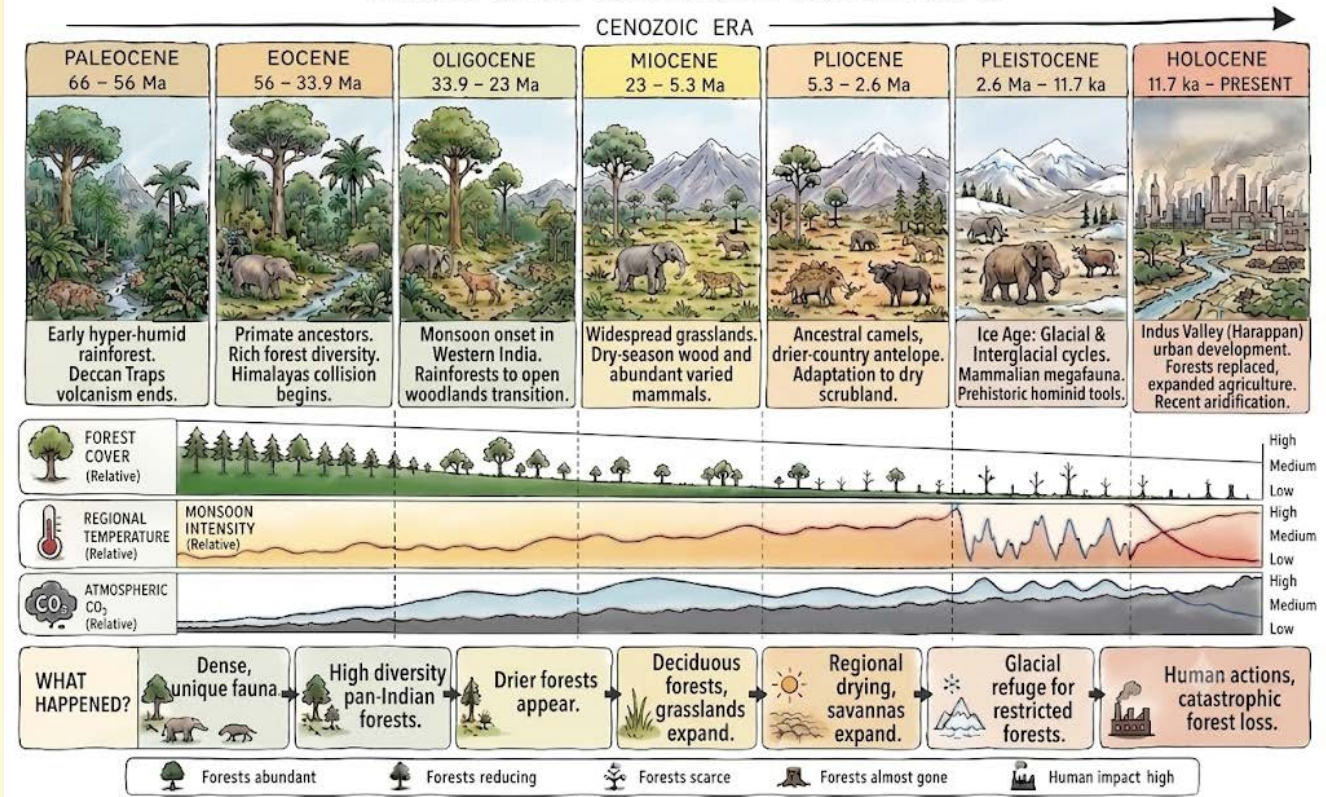


Figure: Fossil wood localities at Habur, Rajasthan, and Lakhanka, Gujarat, India. The lower panel illustrates the fossil woods *Dipterocarpoxylon jammuese*, *Shoreoxylon burmense*, and *Hopenium pondicherriense*.

FOREST DYNAMICS IN WESTERN INDIA: CENOZOIC ERA TO PRESENT

CHANGING CLIMATE CONDITIONS AND ECOSYSTEM SHIFTS



How Climate and Tectonics Reshaped Western India

The story of western India's vanished rainforests cannot be understood without looking at the remarkable geological journey of the Indian plate, and the shifting climates it experienced along the way. Once part of the southern supercontinent Gondwana, India broke away and drifted northward, eventually colliding with Eurasia. This collision reshaped the region, driving the uplift of the Himalaya and Tibetan Plateau and profoundly influencing atmospheric circulation and the Asian monsoon.

At the same time, Earth's climate underwent a dramatic transformation. The warm, greenhouse conditions of the early Cenozoic eventually gave way to a long cooling trend, marked by the gradual formation of Antarctic ice sheets. These large-scale climatic shifts were reflected in India's vegetation.

Fossils of humid-tropical plants, including members of Dipterocarpaceae, show that warm and wet forests once extended across parts of the Indian subcontinent that are no longer able to support such vegetation.

Because rainforest species rely just as heavily on moisture as on warm temperatures, tectonic and atmospheric shifts proved decisive. The uplift of the Himalayas and Tibetan Plateau altered monsoon dynamics, while falling atmospheric carbon dioxide, tectonic reorganization, and weathering fostered increasingly seasonal, arid conditions, particularly across western India.

For plants adapted to humid forests, this was a profound environmental change. The forest did not simply vanish overnight. Instead, the climatic space in which they could survive gradually became smaller. Some populations could persist where moisture remained available, while others disappeared from regions that became too dry.

When the Climate Changed, the Forest Moved

Plants are closely tied to their surroundings. Temperature, rainfall, humidity, soil, seasonality and the availability of suitable habitat all influence where a species can survive. So, when the climate shifts, how does a forest respond?

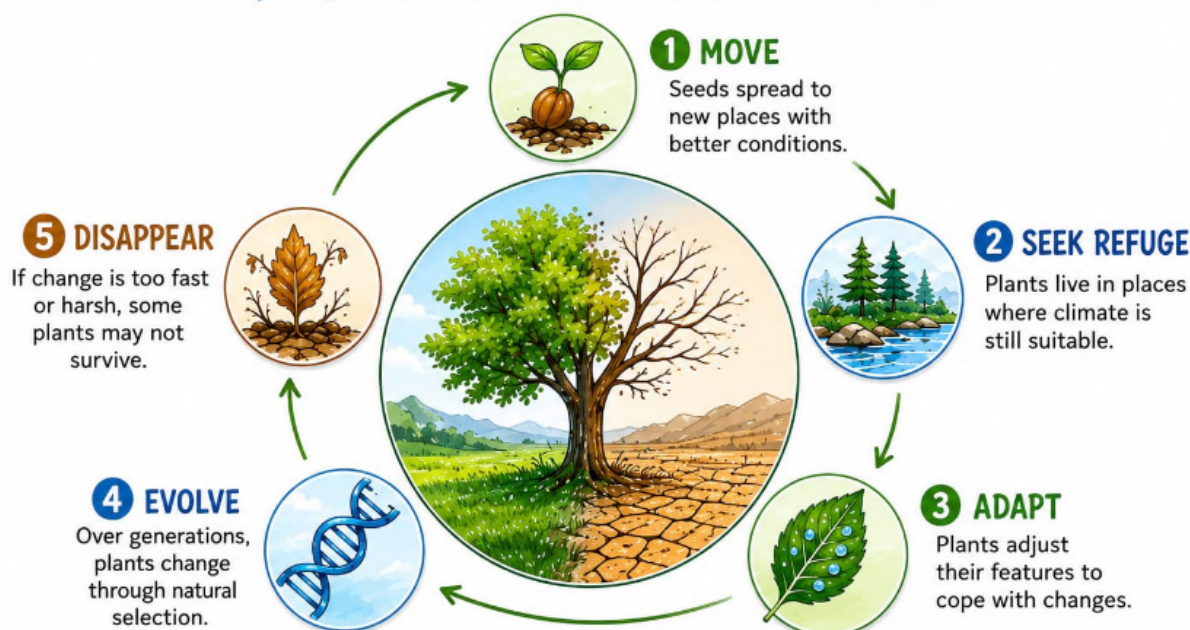
Unlike animals, a tree cannot simply uproot itself and walk away from an encroaching desert. Instead, forests can move across generations. Seeds carried by wind, water and animals can establish new populations in places where conditions are more favourable. Over time, these new populations can gradually shift the geographical range of a species. But movement is not the only option. A vast humid forest does not necessarily disappear all at once. As the climate becomes drier, moisture-loving trees may retreat into smaller pockets where suitable conditions persist, perhaps along rivers and wetlands, or in other areas that remain relatively cool and moist. These surviving pockets, known as refugia, can provide temporary

lifelines for populations as the surrounding landscape becomes increasingly unsuitable.

Over time, however, refugia can become isolated from one another. Populations that were once connected may find themselves separated, reducing genetic exchange between them. If this isolation persists for long enough, populations can diverge and, over evolutionary timescales, contribute to the formation of new lineages.

Plants can also respond through adaptation. Within a population, some individuals may naturally possess traits that make them better able to cope with heat, drought or prolonged dry seasons. Smaller leaves, deeper or more extensive root systems, and greater water-use efficiency can all influence a plant's ability to survive environmental stress. If such traits have a genetic basis, natural selection can favour them over generations. But adaptation and migration have their limits. If the environment shifts too radically and no suitable habitat is within reach, a species will simply fade from the landscape.

PLANTS WAYS TO SURVIVE CLIMATE CHANGE



As the region became increasingly arid, these trees disappeared from Rajasthan. Yet, this was not the end of their story. They survived in the remaining humid tropics of Asia.

When Climate Changes Faster Than Plants Can Follow

The fossil records offer a remarkable window into how plants respond to a shifting world. But, there is a major difference between the climate shifts of the geological past and the climatic crisis we face today: the speed at which change is occurring. During the Paleogene and Neogene, major environmental transformations unfolded over thousands to millions of years, giving forests the time they needed to migrate, adapt, or evolve. Today, human-driven greenhouse gas (GHG) emissions are warming the planet at a rate not seen in the past 10,000 years. The climate is moving faster than the species can follow.

This creates a growing mismatch between the pace of climate change and plants' ability to respond. As

seen with the historical disappearance of *Dipterocarpus* from western India, plants unable to adapt or migrate face local extinction. Plants form the foundation of almost every terrestrial food chain, so changes in plant communities can trigger a chain reaction throughout the ecosystem. The loss of even one tree species can affect seed dispersal, pollination, and the animals that depend on it for food and shelter. The fossil story of *Dipterocarpus* is, therefore, not simply a record of a vanished past; it is a warning of how rapidly climate change could reshape, and potentially destabilise, modern ecosystems.

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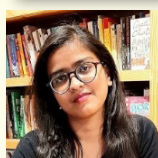
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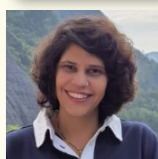
Samiksha Shukla is a research scholar at the BSIP, Lucknow, and the Academy of Scientific and Innovative Research (AcSIR), India. Her research focuses on Cenozoic plant megafossils, palaeobiogeography, and palaeodiversification, employing systematic and phylogenetic approaches.



Vikram Singh Thakur is a research scholar at the Department of Botany, University of Lucknow, Lucknow, pursuing doctoral research at the BSIP, Lucknow. His research focuses on Cenozoic plant-insect interactions, their responses to climatic change, and the implications for ancient ecosystem dynamics.



Kajal Chandra is working as a Research Associate (BSRA) at the BSIP, Lucknow. Her research focuses on elucidating the evolutionary history of angiosperms, with particular emphasis on their spatio-temporal origin, patterns of diversification, and responses to varying climatic and tectonic regimes.



Anumeha Shukla works on plant fossils to understand the evolution and diversification of angiosperms and their responses to climate change since the Cenozoic Era. Her research on early Palaeogene sequences of the Indian subcontinent provides key insights into past floristic exchanges and intercontinental palaeobiological connections.

Decoding the past Biological Carbon Pump and Oceanographic conditions through Diatoms of the Southern Ocean

Aditi Nautiyal, Sunil Kumar Shukla and Rahul Mohan

OCEANS are an important component of the global carbon cycle and play a major role in regulating the amount of carbon dioxide (CO_2) in the atmosphere. Presently, the oceans absorb 25 to 30% CO_2 generated by human emissions and about 90% of the excess heat trapped in earth's atmosphere in the form of greenhouse gases. However, heat and carbon dioxide is not stored uniformly everywhere in the ocean and depends on various factors, such as ocean circulation, temperature, nutrient dynamics, biological productivity and vertical exchange.

The polar oceans, especially the Southern Ocean (SO) encircling Antarctica, plays a major role in regulating the Earth's climate because of its ability to store and exchange significant amount of heat and CO_2 with the atmosphere. This takes place through two major mechanisms, the physical and the biological pump. The physical pump is driven by global ocean currents through differences in temperature and salinity. This *thermohaline* circulation forms a nexus of surface, intermediate and bottom water currents that connect the global oceans and facilitates distribution of heat and nutrients. Originating in the polar oceans, cold saline dense water masses sink to great depths in the ocean forming bottom water. These water masses travel along the base of the ocean basins for thousands of years, accumulating nutrients and carbon dioxide within it. They remerge at the surface through a process called upwelling when atmospheric winds cause a divergence in surface currents and facilitate the exchange of carbon dioxide with the atmosphere. The Antarctic Circumpolar Current (ACC) is the main

driver of this physical pump in the SO. It is the largest and the strongest ocean current on Earth. Driven by the Southern Hemisphere Westerly Winds (SHWW), the ACC flows uninterrupted around Antarctica and connects the Atlantic, Pacific and Indian Ocean basins. Within it lie several major oceanic fronts namely the Sub-Tropical Front (STF), Sub-Antarctic Front (SAF), Antarctic Polar Front (APF) and the Southern Antarctic Circumpolar Current Front (SACCF), along a north-south transect (Figure 1A). These fronts separate water masses with different temperature and salinity characteristics and, thus, act as boundaries of narrow ecological zones that shift in response to changes in ocean circulation.

The biological pump exports carbon to the deep ocean through its photosynthesizing algae. In the sunlit upper 100m of the water column, these phytoplankton utilize the carbon dioxide and nutrients to build up biomass and form the base of the oceanic food web. The physical pump supplies nutrient rich waters to the surface through upwelling which fuels the productivity of these phytoplankton. Diatoms are the microscopic phytoplankton made up of silica (Figure 1B) that dominate primary productivity in the SO. Some of the carbon is used to build silica shells, some respired back into the ocean as carbon dioxide and some ultimately sinks to the seafloor as excreta. Dead algae that are able to escape decomposition and dissolution to reach the seafloor, get preserved in the ocean sediments, thus, removing this carbon from the natural cycle for a long time. Thus, diatoms play a key role in the biological carbon pump by utilizing carbon dioxide and nutrients

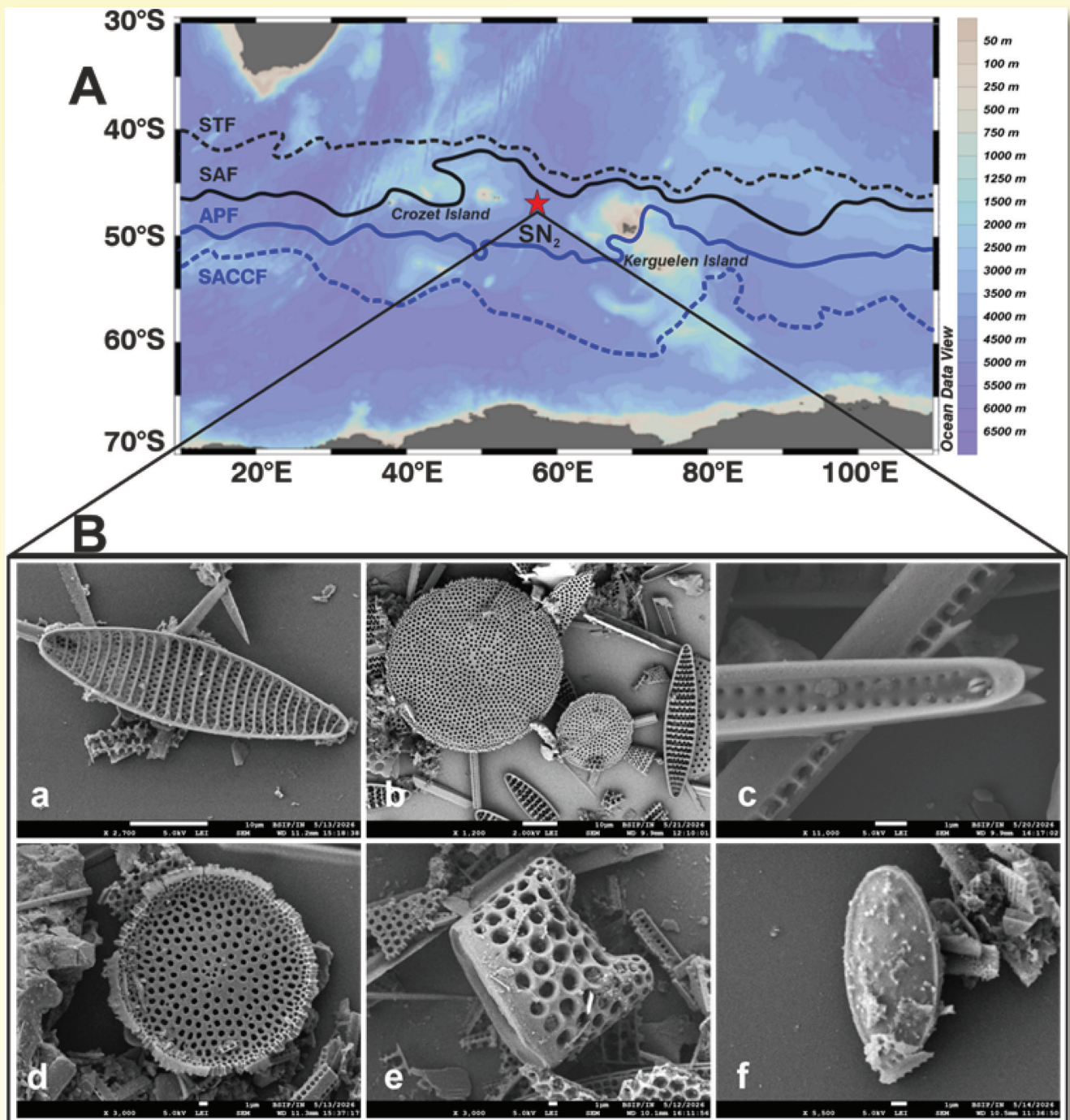


Figure 1 (A) The location of the studied sediment core SN₂ (red star) is shown from the Polar Front Zone of the Indian sector of the Southern Ocean. Positions of the subtropical front (STF – black dotted line), the Sub-Antarctic Front (SAF – black solid line), the Antarctic Polar Front (APF – blue solid line), and the southern Antarctic Circumpolar Current Front (SACCf – blue dotted line) are also shown after Park et al. (2019). The map is prepared using the Ocean Data View software (Schlitzer, 2026). (B) Scanning Electron Microscopy (SEM) images of significant marine diatom species found in sediment core SN₂ from the Indian Polar front Zone. (A) *Fragilariopsis kerguelensis*, (B) *Thalassiosira lentiginosa*, (C) *Thalassiothrix antarctica*, (D) *Thalassiosira antarctica*, (E) *Eucampia antarctica* and (F) *Chaetoceros* resting spores.

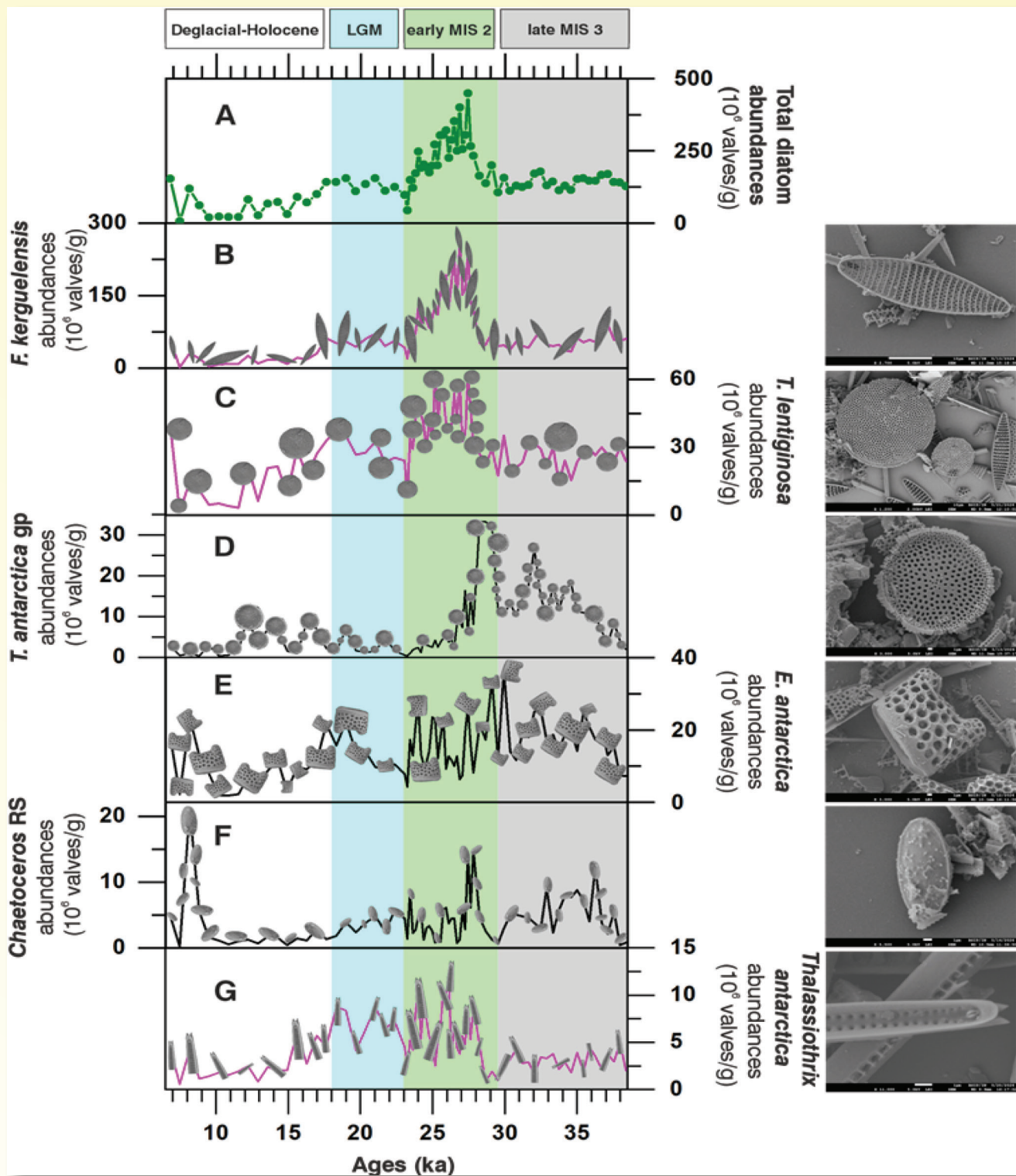


Figure 2. A representation of diatom productivity record in sediment core SN₂ for the past ~40 ka, which depicts the total diatom abundances (A) and absolute abundances of major diatom species *Fragilariopsis kerguelensis* (B), *Thalassiosira lentiginosa* (C), *Thalassiosira antarctica* group (D), *Eucampia antarctica* (E), *Chaetoceros* resting spores (F), and *Thalassiothrix antarctica* (G). The highlighted periods show late Marine Isotope Stage (MIS) 3 (grey), early MIS 2 (green), and the Last Glacial Maximum (cyan).

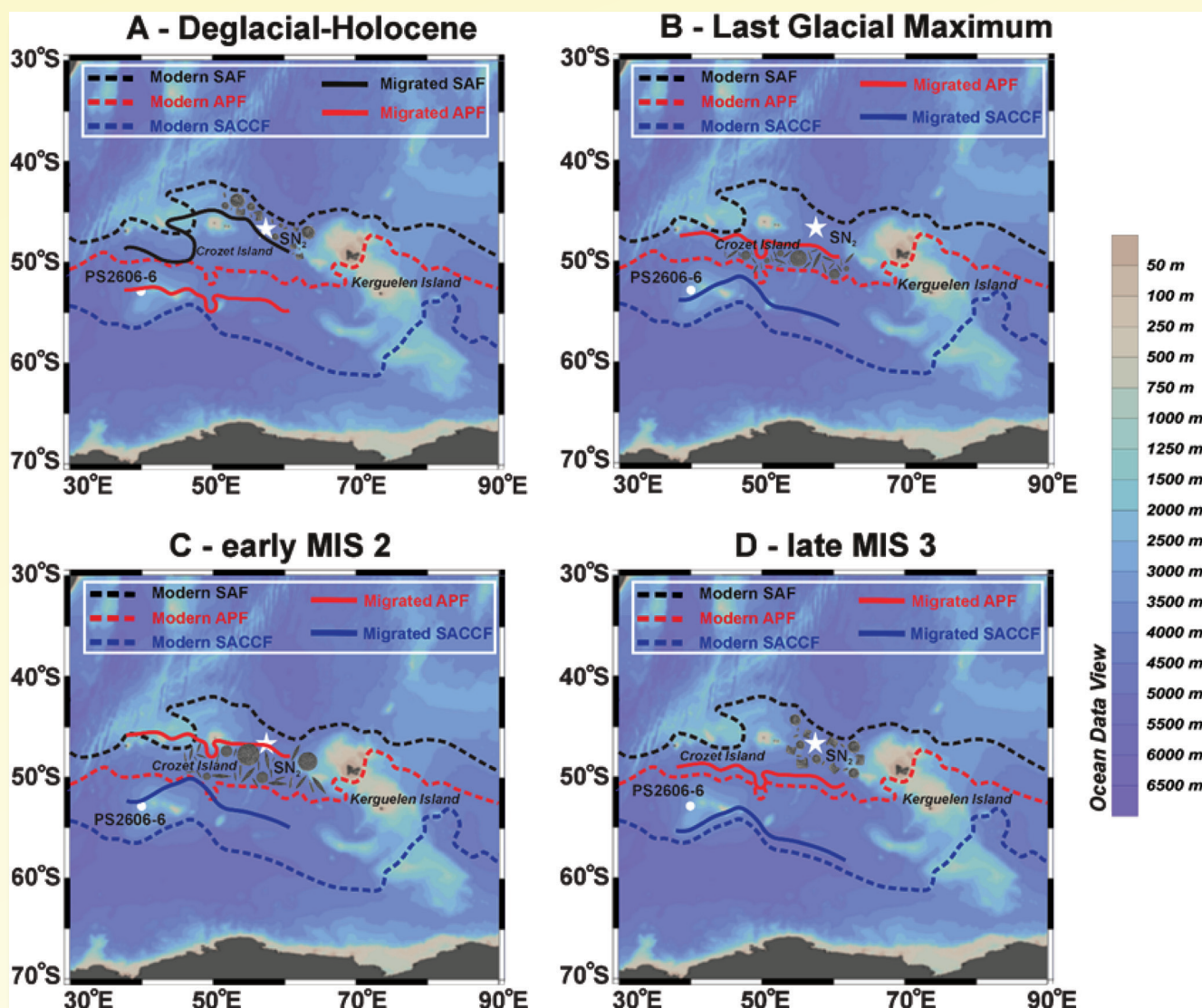


Figure 3. Schematic representation of interpreted front migration based on diatom productivity and the proposed APF index data in core SN₂, shown in maps across the deglacial-Holocene (A) and the glacial period: the Last Glacial Maximum (B), early Marine Isotope Stage (MIS) 2 (C), and late MIS 3 (D).

through photosynthesis and aiding in the export and burial of organic carbon and biogenic silica to the deep ocean. However, diatom productivity depends on the availability of nutrients, such as nitrate, silicate, iron, as well as light.

JH Martin, in 1990 gave the popular Iron Hypothesis stating that iron availability limits phytoplankton productivity. He described the Southern Ocean as a High Nutrient low Chlorophyll (HNLC) region, having plenty of essential nutrients like nitrate and phosphate, but lack enough iron for the algae to thrive. Iron is an essential micronutrient

required for photosynthesis and other cellular processes. Thus, a majority of these nutrients remain unutilized in the absence of iron in the Southern Ocean. “Give me half a tanker of iron, and I will give you an ice age” – this famous quote by Martin describes the importance of iron in controlling marine productivity. According to him, adding iron to the ocean would increase primary productivity. Phytoplankton would consequently utilize the carbon dioxide and export it to the deep ocean. This would ultimately cause a reduction in the atmospheric carbon dioxide concentration and lead to a cooling

effect in the absence of this major greenhouse gas. Subsequent research found that during the glacial periods, atmospheric dust fluxes to the Southern Ocean were higher than average. Antarctic ice-cores and marine sediment cores record high deposition of dust containing iron during glacial periods relative to present conditions. This was associated with expanded dust sources due to increase in aridity, stronger winds and enhanced glacial erosion.

Despite this, the APF zone is characterized with high diatom productivity owing to high iron availability. Fronts are associated with upwelling and mixing promoted by strong currents. This brings nutrient rich deep waters, including iron and silica to the surface which supports the efficient growth of diatoms. The 'silica belt' is a consequence of this increased diatom productivity, formed when diatoms grow and sink, their silica-rich remains contribute to the export of biogenic silica to the deep ocean and gets preserved in sediments. This surplus utilization of silicic acid at the APF for diatom growth can substantially deplete silicic acid as water masses are exported northward through ocean currents. Since diatoms simultaneously respond to and modify the availability of silicic acid, changes in their abundance and productivity can provide valuable information about past changes in nutrient supply, ocean circulation and climate.

But these fronts and the winds that drive them, are not fixed. They migrate in response to change in Earth's climate, particularly temperature. Research into past glacial-interglacial periods suggests that the ACC, and the APF shifted several degrees of latitude owing to the warming and cooling of the ocean and the atmosphere. A northward-moving front during the glacial periods can bring cold, nutrient-rich southern waters into northern latitudes that are normally influenced by warmer waters. Conversely, warmer waters from northern latitudes migrate to the South during interglacial periods. This can alter the supply of nutrients, such as iron and silicic acid to surface waters and, in turn, influence where and how strongly diatoms grow. Previous studies from deep ocean sediment cores show that such frontal movements

have occurred repeatedly in the past and can be reconstructed using changes in diatom assemblages preserved in the sediments.

In this context, we analysed a sediment core SN₂ from the Indian Polar Front Zone (PFZ) in the vicinity of Crozet and Kerguelen Plateaus (Figure 1, Nautiyal et al., 2026). This region of shallow bathymetry and volcanic source rocks is known to bring about natural iron fertilization leading to diatom blooms in present day conditions. We analysed fossil diatoms, accumulated through time in the sediment layers, to quantify diatom productivity for the last ~40,000 years for sediment core SN₂. Our objective through this study was to see (i) whether the glacial-interglacial productivity in the Indian PFZ correlates with dust bearing iron/ natural iron fertilization and (ii) what was the role of frontal migration in modulating the glacial-interglacial diatom productivity.

Diatom productivity and palaeoceanographic conditions in the Indian Polar Front Zone

- Ages of sediment core SN₂ span the last 6.7–38.3 ka (~40ka). The period between 18–40 ka is considered as the glacial period while the period between 18–6.7 ka is considered as the interglacial period (Deglacial-Holocene). The glacial period is subdivided into late Marine Isotope Stage (MIS) 3 (38.3–29.5 ka), Early MIS 2 (29.5–23 ka) and the Last Glacial Maximum (LGM, 23–18 ka).
- Based on previous studies, high diatom productivity should be found in sediment core SN₂ during the last glacial period owing to readily available iron through aeolian dust fluxes or through northward APF migration that supplied the nutrients through upwelling. Interestingly, a heterogeneous pattern of glacial diatom productivity was observed in core SN₂. Total diatom abundances were highest during early MIS 2 and lowest during the deglacial-Holocene periods, with lower intermediate values during late MIS 3 and the LGM (Figure 2). This was at odds with the previous studies with a simple relationship with aeolian dust and iron fluxes

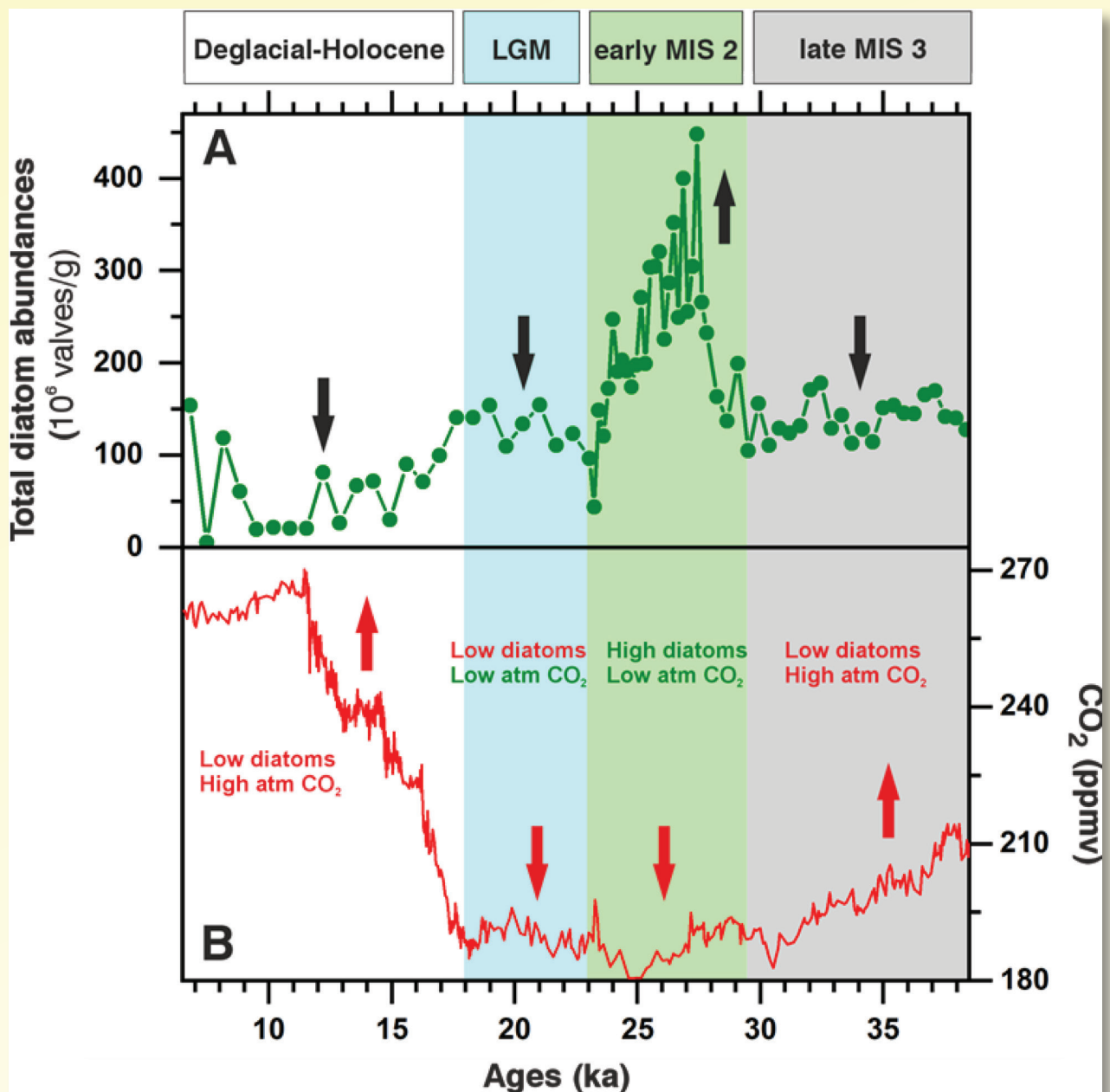


Figure 4. Comparison of diatom productivity record of sediment core SN₂ (A) with EPICA Dome C composite CO₂ records (B, Bereiter et al., 2015) for the last ~40ka. The highlighted periods show late Marine Isotope Stage (MIS) 3 (grey), early MIS 2 (green), and the Last Glacial Maximum (cyan).

which prompted us to explore other possible mechanisms.

- The statistical technique of Principal Component Analysis (PCA) was applied to the diatom productivity data to determine which out of the 31 diatom species contributed significantly

to diatom productivity in core SN₂ over the last ~40ka. PCA results revealed six significant diatom species that contributed to the total diatom abundances. These species were then grouped into Polar Open Ocean Zone (POOZ) group diatoms and Coastal Planktonic group diatoms, based on

their ecological preferences, such as temperature range, distribution, etc. POOZ group consisted of *Fragilariopsis kerguelensis*, *Thalassiosira lentiginosa* and *Thalassiothrix antarctica* (Figure 1B) while the coastal planktonic group included *Thalassiosira antarctica*, *Eucampia antarctica* and *Chaetoceros* resting spores (Figure 1B). POOZ group diatoms are representatives of the Polar Open Ocean Zone between the APF and SACCF. These diatoms represent growth in Southern nutrient rich waters supplied through upwelling. The coastal planktonic group diatoms on the other hand reflect growth in a stratified water column, devoid of nutrient rich upwelled deep waters. The total diatom abundances and the POOZ group diatoms showed a similar pattern from late MIS 3 to the deglacial-Holocene periods. Conversely, POOZ group diatoms were inversely correlated and showed an opposite pattern to the coastal planktonic group diatoms in core SN₂ over the studied period. Thus, it was evident that the diatom productivity from late MIS 3 to deglacial-Holocene periods was controlled by northward and southward migration of the APF and with it, the deep nutrient rich upwelled waters.

- To infer and track the past position of the APF, we used a new metric called the APF index which is the cumulative relative abundance of the POOZ group diatoms found in sediment core SN₂. The APF index values suggested that early MIS 2 was characterized by efficient northward APF migration, when APF was at the core site of SN₂ (Figure 3). This northward migration brought with it the nutrient rich deep waters to the surface through upwelling, supporting high diatom productivity. In contrast, late MIS 3 was characterized by inefficient APF migration while during the LGM, due to reduced upwelling and more stratified conditions, diatom productivity was lower and comparable to that of late MIS 3 (Figure 3). On comparison with global climatic records, it was observed that diatom productivity during early MIS 2 and deglacial-Holocene periods aligned well with high/low dust and iron

fluxes respectively. However, diatom productivity during late MIS 3 and LGM showed disconnection with dust and iron fluxes where lower diatom productivity was recorded despite higher dust and iron compared to deglacial-Holocene period.

Implications for glacial-interglacial atmospheric CO₂

- Strengthening of the biological carbon pump in the Southern Ocean through an increase in productivity during the last glacial period (40-18ka) has been proposed to have resulted in a 15-20 ppmv decrease in atmospheric CO₂. Diatom productivity in core SN₂ was found to be consistent with atmospheric CO₂ records, where the high productivity during early MIS 2 coincided with a decrease in atmospheric CO₂ by an average of ~10 ppmv relative to late MIS 3, which was characterized by lower productivity (Figure 4). Although LGM shows low diatom productivity, atmospheric CO₂ levels comparable to those of early MIS 2 are observed. This can be attributed to the more stratified water column which prevented the release of deep carbon to the atmosphere. Similarly, lower diatom productivity during the deglacial-Holocene periods correlates with higher atmospheric CO₂ concentrations and agrees with higher deglacial-Holocene diatom productivity in the Antarctic zone of the SO, when the ACC shifted southward.
- The paradox of deep-water upwelling where it supplies increased nutrients so as to strengthen the biological carbon pump but also bring carbon rich deep waters to the surface that eventually raise atmospheric CO₂ through outgassing, counteract in the Southern Ocean. Therefore, a northward frontal migration coupled with reduced upwelling and stratified conditions may have reduced atmospheric CO₂ during the glacial periods, such as the LGM in the Indian sector of the SO. Thus, the heterogeneous patterns of diatom productivity during the last glacial period explain how ACC driven frontal migration and nutrient availability

help in shaping diatom productivity in the Indian sector of the SO. This study provides important insights into the role of diatoms in modulating the strengthening or weakening of the biological carbon pump and ultimately the atmospheric CO₂ over the glacial-interglacial periods.

Relevance to present day climate change

- High resolution quantitative reconstructions of diatom productivity records will be helpful to pinpoint the mechanisms driving the Southern Ocean carbon export during glacial-interglacial periods.

- Past records of diatom productivity can give insights into Southern Ocean's response during abrupt climatic events at millennial timescales.
- Diatom productivity records from a climate sensitive region, such as the Southern Ocean would help in reducing the uncertainty in biological carbon pump feedbacks and improve climate model projections.

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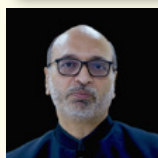
About authors



Ms Aditi Nautiyal is a JRF at the BSIP, Lucknow doing her Ph.D. Her research interests include diatoms, micropalaeontology, palaeoceanography, and paleoclimatology.



Dr Sunil Kumar Shukla is Scientist 'E' at the BSIP, Lucknow. His research interests include diatoms, micropalaeontology, malaeoceanography, and paleoclimatology. His current focus is on the quantitative climate reconstructions from the Indian sector of the Southern Ocean using diatom productivity and diatom derived sea-surface temperature and sea-ice reconstruction.



Dr Rahul Mohan is Scientist 'G' and Group Director of Polar Sciences at NCPOR, Goa. He has specialization in marine micropaleontology, marine geology and palaeoceanography. His current focus is on micropaleontology with special reference to coccolithophores and diatoms.

Reading the Northern Indian Ocean's Diary: What Seafloor Sediments tell us about India's past and future Climate

Syed Azharuddin and Pawan Govil

STAND on any beach along India's eastern or western peninsular coast, and the surrounding Indian Ocean looks timeless and seemingly unchanging. But if you drill beneath the ocean surface, then you will find a different story. Over the past 50,000 years, this ocean has been colder by several degrees, has released vast amounts of greenhouse gases into the atmosphere, and has witnessed the rise and fall of civilizations alongside the strengthening and weakening of the Indian Monsoon rains that sustain a billion people.

By obtaining long marine sediment cores from the Arabian Sea and the Bay of Bengal, we have reconstructed ocean temperature, salinity, productivity, and even ocean acidity, along with past monsoon variations. The study has implications for understanding the monsoon, predicting future climate change, and appreciating just how dynamic the Indian monsoon system is, as well as related changes in the Northern Indian Ocean.

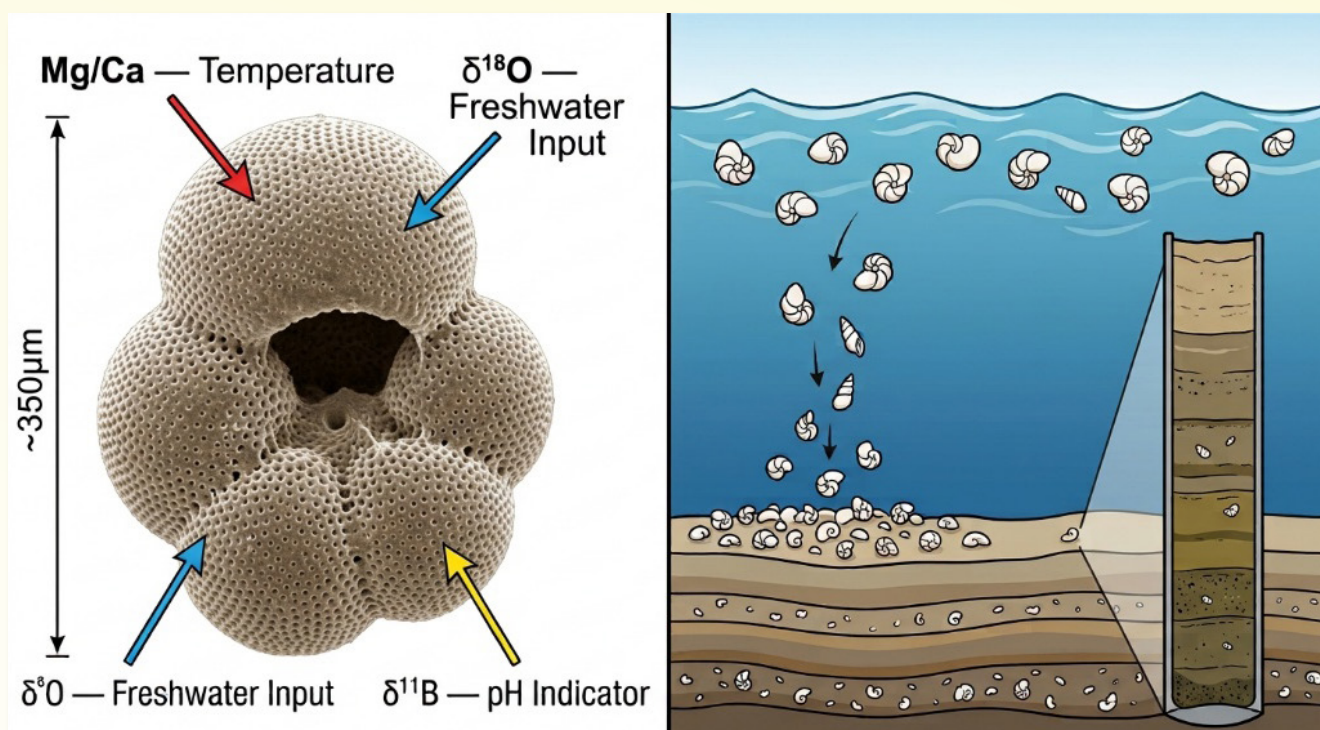


Figure 1. Schematic illustrations of multiproxy analysis based on foraminifera (right) and the marine sediment core collected from sea floor (right).

The ocean thermometer in the tiny shells

The star of our research is a microscopic organism (foraminifera), which is tinier than a grain of sand (Figure 1). These single-celled organisms build shells of calcium carbonate while recording the ambient ocean as they float in the water column. When they die, their shells get buried in the seafloor, accumulating layer by layer over thousands of years, creating a continuous archive of ocean conditions.

Two of our most powerful tools work hand in hand: the Mg/Ca ratio and the oxygen isotope composition ($\delta^{18}\text{O}$) in the shells of planktic (sea surface-dwelling) foraminifera. The Mg/Ca ratio acts like a natural thermometer. The warmer the sea surface, the more magnesium is incorporated into the

foraminifera's shell at the time of their calcification. But temperature isn't the only story locked in the shells of foraminifera. The $\delta^{18}\text{O}$ of foraminifera is influenced by both the water temperature and the $\delta^{18}\text{O}$ of the seawater itself, which changes with global ice volume and local freshwater input from monsoon rains and river runoff. By measuring Mg/Ca to decipher the exact Sea Surface Temperature (SST), we can mathematically remove the temperature effect from the $\delta^{18}\text{O}$ signal. Subsequently, what remains is the $\delta^{18}\text{O}$ of the ancient seawater, which indicates how much freshwater was mixed into the ocean. This is how we track the intensity of past monsoons. Together, these twin proxies allow us to reconstruct not just how warm the ocean was, but also how wet the land was, tens of thousands of years ago.

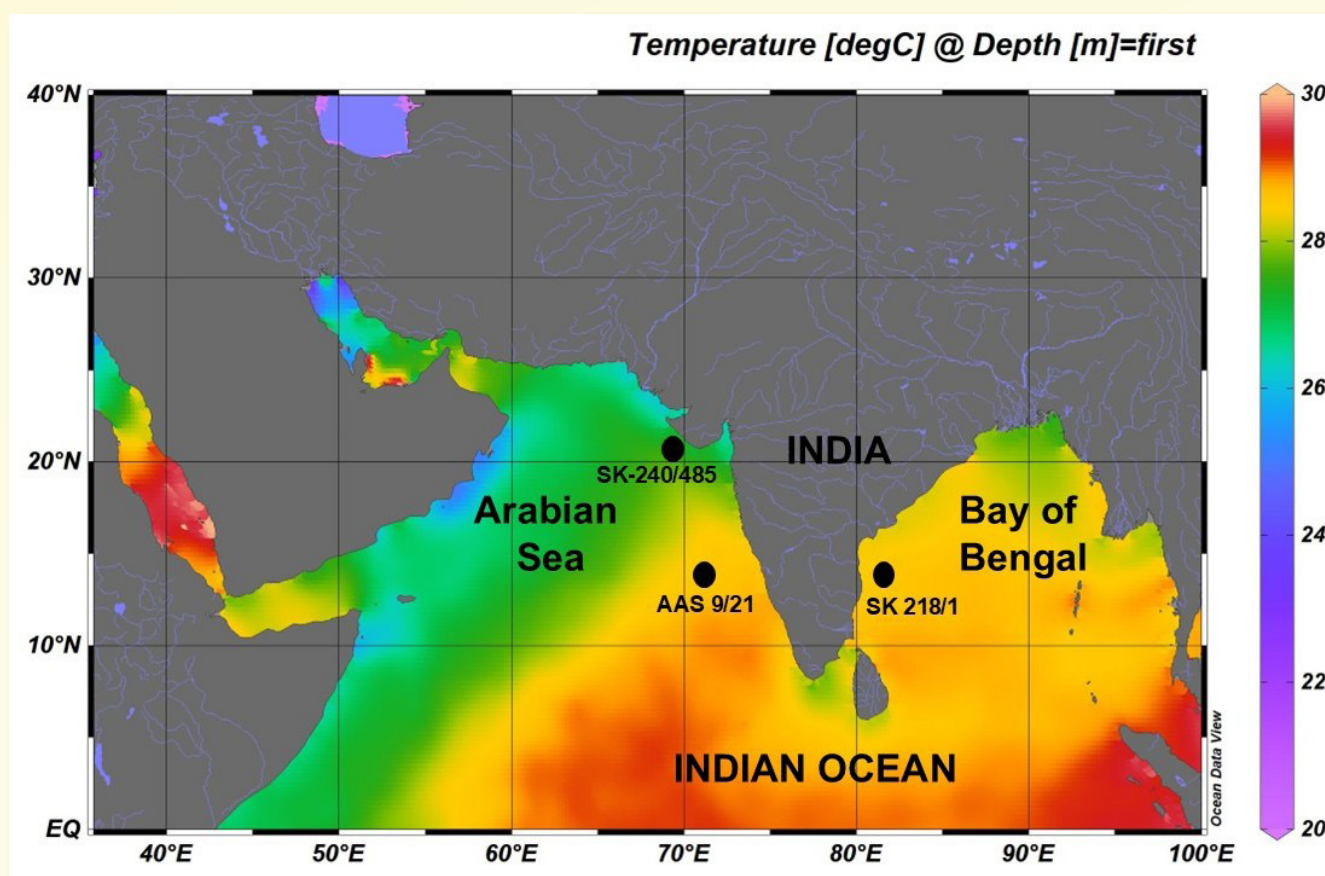


Figure 2. Map of Northern Indian Ocean showing marine sediment cores discussed in this article. The colour scheme represents the modern annual sea surface temperature obtained from World Ocean Atlas 2023.

The cooling history of northern Indian Ocean waters during the Last Glacial Maximum

We conducted a study on evaporation-precipitation changes in the Arabian Sea over the past 68,000 years using a sediment core from the eastern Arabian Sea (AAS9/21) (Figure 2) (Govil and Naidu, 2010). The study suggested that during the Last Glacial Maximum (LGM; around 20,000 years before present), when ice sheets covered much of North America and Europe, the sea surface temperature of the Arabian Sea was $\sim 4^{\circ}\text{C}$ colder than today. Four degrees might not sound dramatic, but in climate terms, it's enormous. This

cooling altered ocean circulation, monsoon rainfall patterns, and marine ecosystems across the region. It also challenges earlier assumptions that tropical oceans remained relatively stable during ice ages. Our data, along with similar findings from the Bay of Bengal, show that the Indian Ocean was significantly affected by glacial conditions. However, it is interesting to note that this cooling wasn't uniform throughout the Northern Indian Ocean.

Subsequently, we applied similar methods, and conducted another study from the Bay of Bengal site SK218/1 (Govil and Naidu, 2011). The study suggested that the Bay of Bengal cooled by about

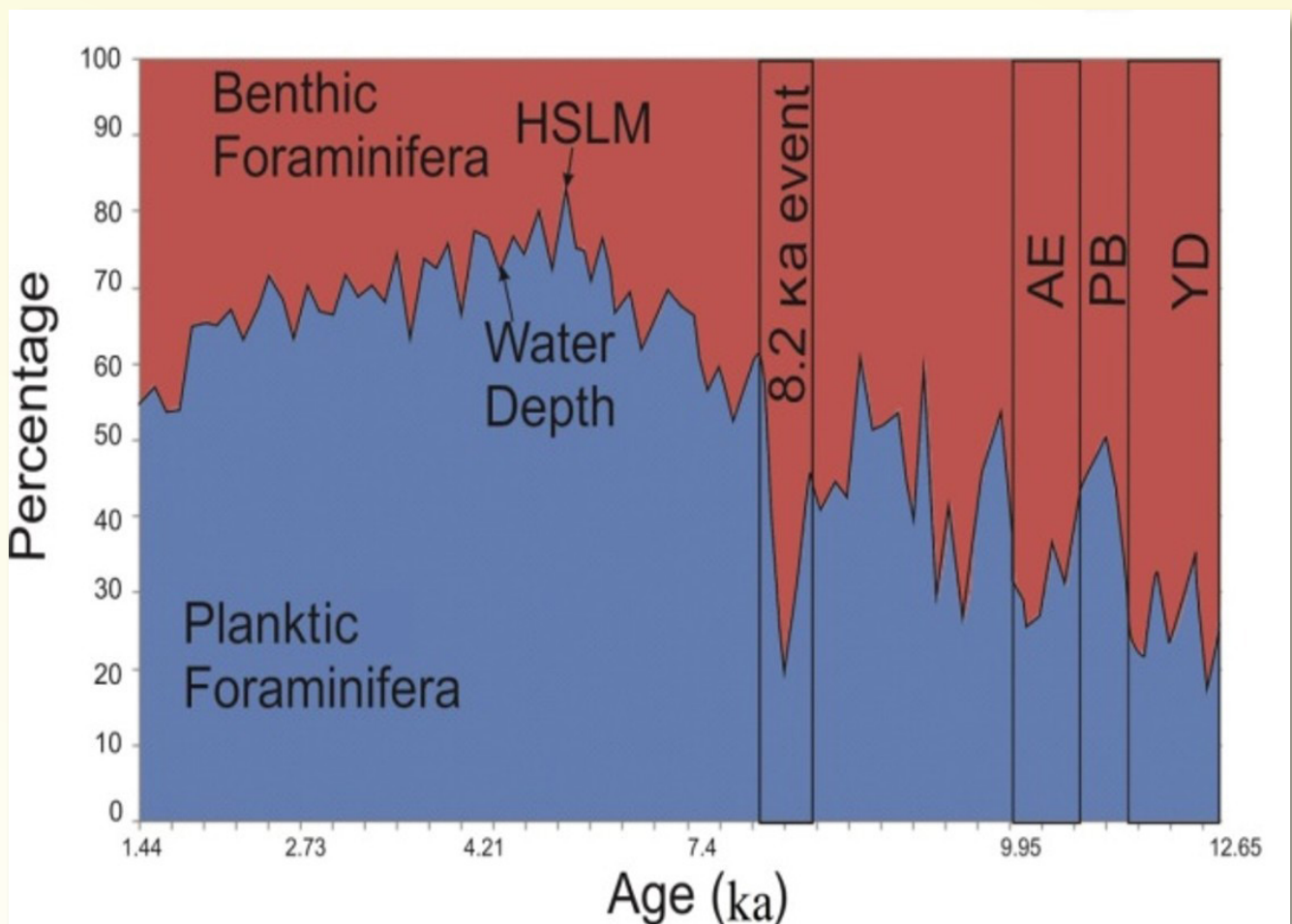


Figure 3. Relative abundance percentage of total planktic and benthic foraminifera population during the last ~ 12000 years at Arabian Sea site SK-240/485. The relative percentage is used as a proxy for relative changes in regional sea level. HSLM (Holocene Sea Level Maximum), AE (Abrupt Event), PB (Pre-Boreal), YD (Younger Dryas). Modified after Azharuddin et al., (2017).

3.2°C during the LGM, which is ~0.8°C less than that observed in the Arabian Sea during the same period. The difference in SSTs between the two basins reflects regional oceanographic processes: the Bay of Bengal receives massive freshwater inputs from rivers, such as the Ganges and Brahmaputra, whereas the Arabian Sea is more influenced by evaporation and upwelling.

Reading the Ocean's Pulse Through Foraminifera Population

Beyond temperature, foraminifera also tell us about ocean productivity i.e. how much foraminiferal life the ocean supported at different times. In a study from the offshore Saurashtra region of the northeastern Arabian Sea (core SK-240/485), we, in fact, studied the census of foraminiferal shells per gram of sediment over a 12,000-year period to understand changes in foraminiferal productivity in the region (Azharuddin et al., 2017). During the Younger Dryas (YD) period (a sudden cold surge around 12,000 years ago) and the early Holocene (10,000 to 8,000 years ago), foraminiferal abundance was remarkably

low. This indicated a "productive collapse," i.e. the ocean lacked sufficient nutrients to support abundant foraminiferal life.

Further investigations of the relative abundance percentage of planktic and benthic foraminifera revealed that during the YD and early Holocene, global sea levels were roughly 40 to 50 meters lower than today (Figure 3). As a result, our core site, now at an 88-meter depth, was located in a shallow coastal environment. The conditions were likely too shallow and turbid for most planktonic foraminifera to thrive. As the ice sheets melted and sea levels rose, the site deepened, and nutrient-rich freshwater from the Indus River began reaching the area, fuelling a surge in productivity during the middle Holocene (8,000 to 4,000 years ago). By the late Holocene (4,000 years ago to present), productivity reached its peak.

This simple story about sea-level rise enabling nutrient delivery in the Arabian Sea reveals how intimately ocean life is tied to glacial-interglacial cycles. It also shows that the offshore Saurashtra region is uniquely sensitive to freshwater discharge from the

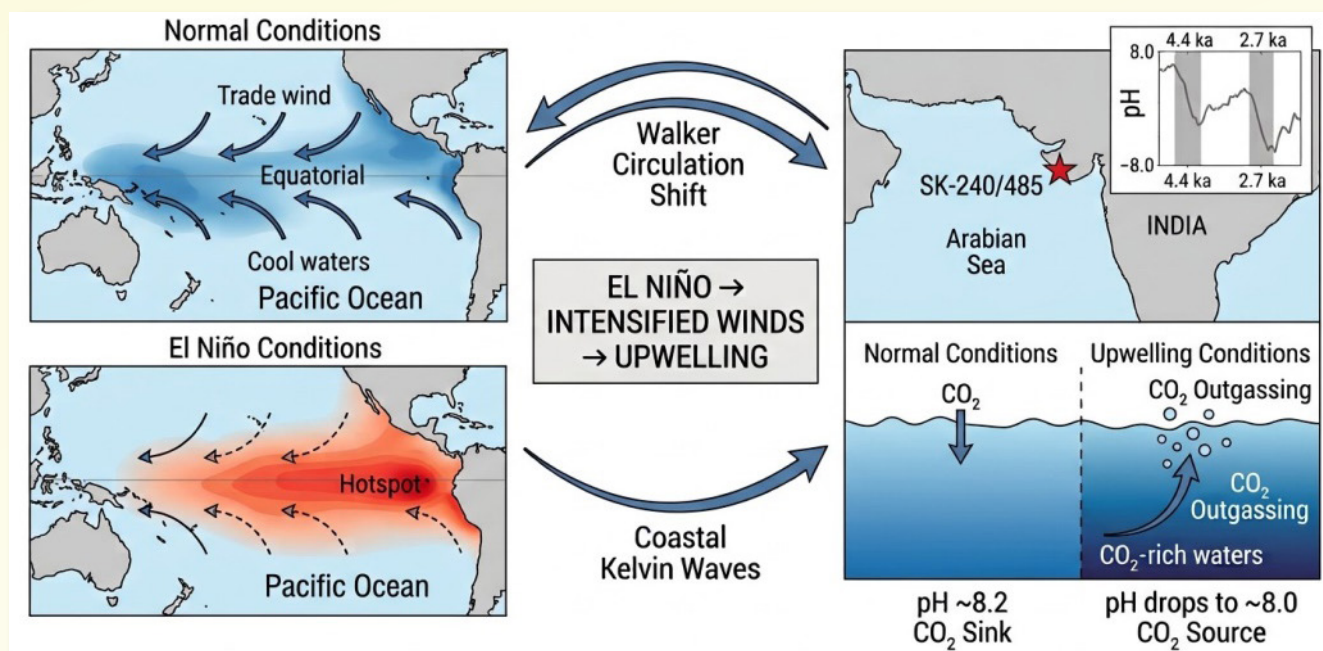


Figure 4. Conceptualised illustration of Climatic and Oceanographic Teleconnections between Arabian Sea upwelling and Climate Oscillations in the Pacific Ocean as explained in Azharuddin et al., (2022).

Indus, making it an ideal place to track monsoon variations.

The Ocean's Litmus Test: Reading pH from Boron Isotopes

Perhaps our most remarkable findings come from an unexpected source: the boron isotopes ($\delta^{11}\text{B}$) locked inside the shells of ancient foraminifera. This technique allows us to reconstruct the ocean's pH as it was thousands of years ago. When seawater absorbs CO_2 from the atmosphere, it becomes more acidic, and its pH drops. As foraminifera build their shells, they inadvertently record this chemical change through the boron isotopes they incorporate. Think of it as a chemical fingerprint: in more alkaline waters (higher pH), the shells contain more of the heavier boron isotope (^{11}B); in more acidic waters (lower pH), they contain less.

We applied this method to reconstruct surface-water pH and CO_2 levels in the northeastern Arabian Sea over the past 8,000 years (Figure 4) (Azharuddin et

al., 2022). We got some very interesting observations about the region's CO_2 source/sink behaviour. During two distinct periods, around 4,400 years ago and again around 2,700 years ago, the region abruptly switched from being a CO_2 sink (absorbing the gas from the atmosphere) to a CO_2 source (releasing it back into the air). Also, during these episodes, the pH of the area dropped by 0.25 units seawater and CO_2 levels increased to as high as 415 parts per million. To put these numbers in perspective: that's comparable to the atmospheric CO_2 and oceanic pH levels we are seeing today, driven by the burning of fossil fuels. As a result, the Arabian Sea outgassed a substantial amount of CO_2 into the atmosphere during those periods.

We further investigated the cause of these abrupt shifts recorded in our data. The evidence pointed towards enhanced upwelling in the region, which brought CO_2 -rich deep-ocean waters to the ocean surface. We further investigated the cause of these abrupt shifts. The evidence points to enhanced upwelling, i.e., the deep, CO_2 -rich waters being brought to the surface. Our comparison with other

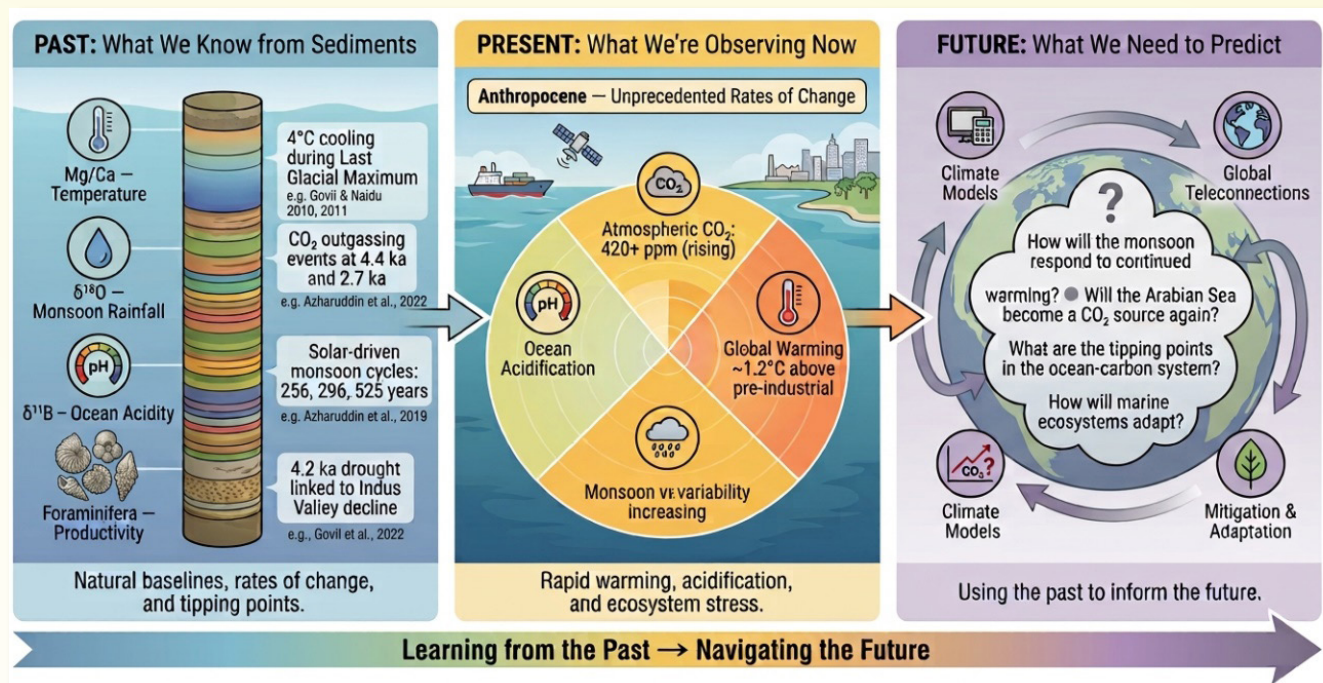


Figure 5. Conceptualised illustration of the role of ocean sediments in reconstructing the past, present and future climate including the inferences from recent studies from our group.

paleoclimate records suggests a link to the Ocean-atmosphere interaction in the Pacific, i.e. El Niño-Southern Oscillation (ENSO) activity. Both episodes coincide with periods of increased ENSO frequency. During strong El Niño events, changes in atmospheric circulation can intensify the winds that drive upwelling along the Arabian Sea coast, bringing nutrient-rich but CO₂-laden waters to the surface.

This finding carries profound significance in the ongoing conversation about climate change. Our data shows that even under natural conditions, the ocean can experience rapid, significant acidification and CO₂ release. Understanding these natural phenomena is essential for predicting how the ocean-carbon system might respond to current human-induced warming (Figure 5).

The Sun's Rhythm: Monsoon Cyclicity and Solar Activity

One of the most fascinating patterns in our data is the presence of cycles i.e. regular, periodic variations

in monsoon strength that align with changes in solar activity.

We used spectral analysis on multiple proxy records (oxygen isotopes, carbon isotopes, nitrogen isotopes, and foraminiferal abundance) from two sediment cores off Saurashtra (Azharuddin et al., 2019). We identified significant periodicities: roughly 256 years, and 1,609 years. We further suggested that these aren't the random noise in our data but each of these cycles point towards a long-term climate phenomenon repeating itself after a certain period. For example: The 256-year cycle matches the De Vries-Suess solar cycle, a known variation in solar output. The 1,609-year cycle aligns with the Bond cycles which represents the cold events in the North Atlantic and have been linked to solar variability. These findings suggest that the solar activity is a primary driver of monsoon variations over centennial to millennial time scales. When the sun is more active, it warms the Indian Ocean and the Tibetan Plateau, enhancing the land-sea temperature contrast that drives monsoon winds. When solar activity wanes, the monsoon weakens.

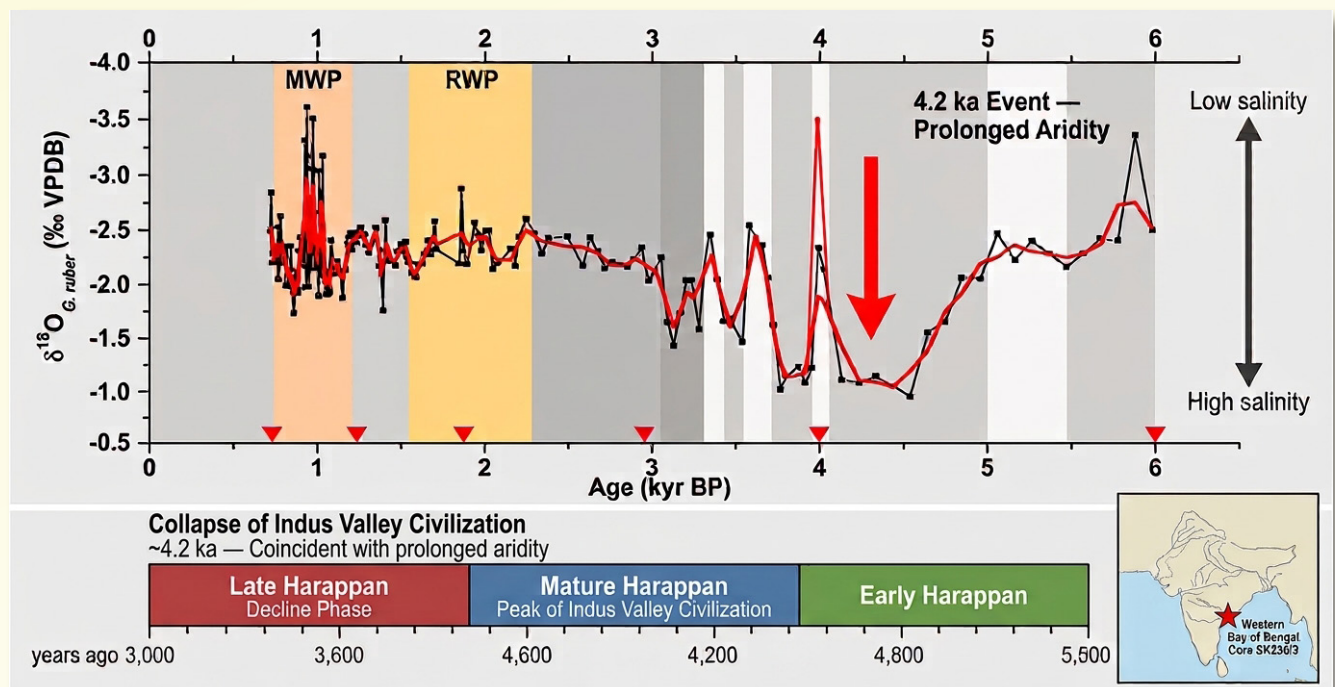


Figure 6. High-resolution 18O record of last ~6000 years from site SK-336/3 showing prolonged aridity in Asian Monsoon around ~4200 years ago (or 4.2 ka) which probably led to the decline of Indus Valley civilisation.. Redrawn after Govil et al., (2022).

We further performed correlation analysis which shows a particularly strong relationship between solar irradiance and monsoon proxies at our NE Arabian Sea core site. This is likely because higher sedimentation rates in shallow waters provide better temporal resolution, capturing solar signals more clearly than deeper, slower-accumulating sediments.

This study gave a profound understanding of the solar activity over the past and could help us predict decadal to millennial-scale monsoon trends. Our study also demarcates that apart from solar activity, ocean circulation, volcanic eruptions, and greenhouse gases also play important roles as fundamental forcing factor.

Why This Research Matters for Today's Climate Challenges

Understanding ancient oceans isn't just an academic exercise, but it directly addresses the most urgent environmental questions of our time. The past is truly the key to the future, and here's why our findings matter:

Establishing natural baselines: To assess how much human activity has altered the climate, we must first know how the climate behaved before industrialization. Our multi-proxy records from the Arabian Sea and Bay of Bengal provide precisely this baseline. They show that even natural variations in monsoon intensity, ocean temperature, and productivity were significant over millennia. Yet, when we compare these natural fluctuations with the changes observed in the last century, the current rate of warming and acidification stands out as unprecedented in the last several thousand years.

Ocean acidification insights: Our boron isotope work revealing abrupt CO₂ outgassing events at 4,400 and 2,700 years ago provides a critical natural analogue. These episodes demonstrate that the ocean-carbon system can change rapidly within centuries in response to natural forcing. The global decline in ocean pH we are witnessing today, driven by fossil fuel emissions, is occurring at a rate at least ten times faster than any natural event we have documented. If natural

events caused measurable ecological stress, what will an anthropogenic acidification event of far greater magnitude and speed do to marine life, particularly shell-forming organisms like corals and plankton?

Climate teleconnections: Our finding that intense upwelling events and CO₂ outgassing coincided with periods of increased ENSO activity highlights the global connectivity of climate systems. As anthropogenic warming is projected to strengthen ENSO variability, the Arabian Sea may experience more frequent and intense upwelling, with cascading effects on regional productivity, fisheries, and carbon cycling. Understanding this link from the past helps us prepare for these potential future changes.

Sea level rise preparedness: Our foraminifera-based productivity records clearly show how past sea level rise transformed the marine ecosystem from a low-productivity, shallow coastal environment in the early Holocene to a high-productivity, nutrient-rich basin in the late Holocene. Today, with sea levels rising again due to melting ice sheets and thermal expansion, similar transformations are underway along India's coasts. By studying the past, we can anticipate how future sea level rise might reshape coastal ecosystems, fisheries, and even the livelihoods of millions of people dependent on marine resources.

One interesting finding was the "4.2 ka event", found in our both Arabian Sea and Bay of Bengal records (Azharuddin et al., 2019; Govil et al., 2022). It was a period of prolonged aridity around 4,200 years ago that we and others have documented across the Northern Indian Ocean. This drought coincides with the decline of the Indus Valley Civilization, suggesting climate change may have played a role in its collapse (Govil et al., 2022) (Figure 6).

In essence, our work is not about escaping into the distant past, it is about grounding our understanding of present-day changes in the long-term context of natural variability. The ocean has been keeping a detailed diary for millions of years. We are finally learning to read it, and what it tells us is both humbling and essential for navigating the uncertain decades ahead.

Conclusion: Listening to the Ocean's Voice

Every time we start sampling a sediment core, it feels like cracking open a time capsule. The microscopic foraminifera shells, the chemical signatures locked in calcium carbonate, the layers of sediments, all have their own language. They speak of glacial cold and interglacial warmth, of monsoons that waxed and waned with the sun's heartbeat, and of oceans which constantly exchange the information with the atmosphere.

Our research in the Northern Indian Ocean has given us a window into India's past climate and a lens for viewing its future. Our research shows that the Indian Ocean is an active driver capable of amplifying or dampening global trends through its own internal dynamics.

Most importantly, we have demonstrated that the ocean remembers. Therefore, if we listen carefully using the tools of modern geochemistry, from Mg/Ca thermometry to boron isotope pH reconstructions, it

will tell us what we need to know to mitigate the future climate. The sea has been keeping a diary for millions of years. It's time we learned to read it.

This article is based on the following research papers from our group:

Govil & Naidu, 2010 (Paleoceanography) <https://doi.org/10.1029/2008PA001687>

Govil & Naidu, 2011 (Quaternary Science Reviews) <https://doi.org/10.1016/j.quascirev.2011.10.004>

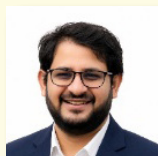
Azharuddin et al., 2017 (Palaeogeography, Palaeoclimatology, Palaeoecology) <http://dx.doi.org/10.1016/j.palaeo.2016.11.018>

Azharuddin et al., 2019 (Geoscience Frontiers) <https://doi.org/10.1016/j.gsf.2019.03.007>

Azharuddin et al., 2022 (Scientific Reports) <https://doi.org/10.1038/s41598-022-07774-4>

Govil et al., 2022 (Journal of Asian Earth Sciences) <https://doi.org/10.1016/j.jseaes.2022.105100>

About authors



Dr Syed Azharuddin is a Senior Lecturer in the Department of Geology at University Malaya, Malaysia. He is a geologist and paleoceanographer. His research focuses on reconstructing past climate and oceanographic variability using geochemical proxies, biomarkers, and microfossils in marine sediment archives.



Dr Pawan Govil is Scientist-F at the BSIP, Lucknow. Holding a doctoral degree in Marine Sciences, he specializes in ocean and polar paleoclimate alongside paleoceanography. His primary research focuses on reconstructing past climate variability by applying advanced biogeochemical and micropaleontological proxies to Indian Ocean and Antarctic Lake sediment cores.

The Story of Karewa Sediments

Binita Phartiyal, Shirish Verma and Rakesh Chandra

WHEN you look at the Kashmir Valley today in the northwestern Himalayan ranges of our subcontinent-its rolling fields, its saffron blossoms, its apple orchards- it's easy to think of it only as a place of beauty and culture. But beneath that beauty lies something far older, far deeper: a silent archive of Earth's history, written not in ink, but in clay, sand, and stone.

These are the Karewas - elevated tablelands that rise like weathered sentinels above the valley floor. In the Kashmiri dialect, *Karewa* means "tableland," or *wuder* in local language. At first glance, they look like simple plateaus or mounds scattered across the valley. But in truth, they are the keepers of Kashmir's prehistoric past, a geological and cultural treasure that tells us not only about the Earth's past, but about humanity's own story in this region.

The scientific story of the Karewas begins in the 19th century. In 1859, a geologist named Godwin-Austen first described these unusual landforms. Later,

in 1878, Lydekker expanded on the observations. But it was in 1939, through the work of de Terra and Patterson, that the Karewas truly came into scientific focus. Their detailed account revealed that these were not just heaps of soil. They were ancient sediments, built layer upon layer across millions of years, a living timeline of Earth processes preserved in the very heart of Kashmir.

Around fifty million years ago, the Indian Plate collided with the Eurasian Plate. The immense forces generated by this collision gave birth to the Himalaya. But mountain building did not end there. Even today, the Indian Plate continues to move northward by nearly five centimetres every year, making the Himalaya one of the youngest and most active mountain belts on Earth. As the Himalaya continued to rise, parts of the crust bent downward, forming an intermontane basin between the Pir Panjal Range and the Greater Himalaya. This depression gradually became the Kashmir Basin-a natural container that



would later host one of the largest freshwater lakes in the Himalaya. Tectonic uplift near Baramulla restricted the drainage of the basin. Rivers flowing from the surrounding mountains began to fill the depression with water, creating a vast freshwater lake. This lake existed for millions of years and received sediments carried by rivers, glaciers, wind, and seasonal floods. Every mountain surrounding the Kashmir Basin contributed sediments to the ancient lake. To the southwest lies the Pir Panjal Range, dominated by volcanic rocks formed nearly 280 million years ago. To the northeast stand the Greater Himalaya, composed mainly of granites, gneisses, and metamorphic rocks. Streams draining these mountains transported rock fragments, clay, silt, and sand into the lake, gradually building the thick Karewa deposits that we see today.

Now with this in the background imagine standing in the Kashmir valley and looking across its 40-kilometer length and 80-kilometer width. What you're seeing is not just a bowl of land, but an ancient intermontane basin, once filled with lakes, rivers and glaciers. Over time, these forces laid down thick blankets of sediment. Today, the Karewas rise as terraces, mounds, and plateaus, sculpted into the valley's panoramic landscape.

The Karewa deposits belong to the Late Pliocene to Quaternary Period, meaning they span from the Pliocene to the Pleistocene epochs - a window of roughly the last four million years. Within this time, Earth saw dramatic changes. Ice ages came and went.

Climates shifted from warm to cold, from wet to dry. And the Karewas recorded it all.

These sediments are about 1,300 meters thick layers of clay, sand, and gravel, with occasional seams of lignite that hint at ancient swamps and forests. They were laid down on much older basement rocks, some Precambrian, some even Mesozoic and fossiliferous.

Geologists divided this vast archive into three great formations: the Hirpur, the Nagum, and the Dilpur. Each one tells a chapter in Kashmir's geological history. The Hirpur Formation- its type sections defined along the Rambaria River, holds within it members named Dubjan, Rambaria, and Methwonian. These units reveal the earliest parts of the Karewa story. The Nagum Formation, identified near Qasba Nagum, is represented by the Shupiyan, Pampor, and Krungus members. Here, we see changes in sedimentation, the whispers of shifting rivers and lakes. And finally, the Dilpur Formation, the youngest, named after the village Dilpur. Its sediments are dominated by loess- the fine dust carried by winds, layered with ancient soils. This loess-paleosol sequence is extraordinary: it links Kashmir directly with the famous loess deposits of China, both serving as archives of global climate fluctuations.

What makes the Karewas so remarkable is not just their thickness or their beauty, but the story they preserve about climate. For nearly four million years, the Karewas have captured evidence of glacial and interglacial cycles, of warmer interludes and colder



episodes. They record rainfall patterns, river flows, and even the fingerprints of earthquakes. In a recent study by Verma et al., 2026 a & b the climatic variability over the past 41.8 ka in the Karewa sediments of the Kashmir Valley has been reconstructed using a multi-proxy approach. Results reveal a dynamic interplay between the Westerlies and the Indian Summer Monsoon (ISM), with their alternating dominance shaping the valley's palaeoclimate and thirteen distinct climatic zones have been identified. Westerly influence prevailed during 40.6–38.2 ka, 34–29.4 ka, 28.5–27 ka, 24–16.5 ka, 11.9–10.3 ka, and 9.1–7.1 ka, while ISM dominance occurred during 38.2–34 ka, 29.4–28.5 ka, 27–24 ka, 16.5–11.9 ka, 10.3–9.1 ka, and 7.1–1.4 ka. Inside these sediments, fossils of plants and animals survive, providing direct evidence of how life adapted to shifting climates. Scientists have studied these records for decades, piecing together a paleoclimate narrative that ties Kashmir to global climatic events. Think of the Karewas as an ancient diary, its pages made of clay, silt, sand, gravel. Each entry, each layer, speaks of a different world. A wetter age, perhaps, with lush vegetation. A colder time, with ice nearby. A period of dryness, with dust carried by strong winds. In the silence of their sediments, the Karewas preserve the voice of Earth's memory.

But the Karewas are not just about rocks and fossils. They are also about people. For archaeologists, these sediments are a treasure trove. Within their layers, they've found tools that span the ages, from the Paleolithic to the Neolithic. Stone needles,

awls, arrowheads, chisels, and hoes - all telling of communities that lived, hunted, and farmed in the valley thousands of years ago. Pottery too- thick coarse grey ware, fine grey ware, gritty red ware, each shard a fragment of cultural history. Therefore the Karewas are not just a geological archive, but also a cultural archive too. They tell us about how people adapted to their environment, how they shaped the land, and how the land shaped them. The Neolithic site of Burzahom exhibits continuous habitation for over three millennia, dating back to 3000 BCE, in four distinct cultural sequences: Neolithic I (Aceramic), Neolithic II (Ceramic), Megalithic, and Early Historic. The Northern Neolithic culture of Burzahom is similar to contemporary cultures of the Indus Valley, Swat Valley, Ghalghai, Sarai Kola and Karua (Tibet), indicating cultural exchange (Dwivedi, et al., 2025).

Even today, the Karewa soil sustains life. They are rich, fertile, and famous for nurturing Kashmir's most cherished crops. This is where the valley's world-renowned saffron grows-the deep purple strands that have for centuries been more valuable than gold. Alongside saffron, the Karewa soils support almonds, apples, apricots, and pears. So when you bite into a crisp Kashmiri apple, or savor the delicate aroma of saffron tea, you are, in a way, tasting the legacy of the Karewas.

And yet, this priceless archive, this foundation of culture and agriculture, is under threat. Modern development has not been kind to the Karewas. Across Pulwama, Budgam, and Baramulla, huge portions



have already been levelled. Bulldozed for brick kilns. Excavated for construction clay. Razed to make way for highways, rail lines, and ring roads. The Jammu-Srinagar highway, the Qazigund-Baramulla rail line, the four-lane projects- all have bitten deep into the Karewas, often without considering their geological or cultural importance.

In just a few decades, plateaus that took millions of years to form have been flattened, their stories lost forever. What remains is not a living archive, but a scarred landscape, stripped of memory. The Karewas are not just piles of dirt to be dug up for bricks. They are among the most important continental paleoclimate archives in Asia. They are windows into Earth's climatic past, crucial for understanding how our planet has changed, and how it may change again in the future.

The Karewas must be viewed as geoheritage sites- unique geological features that deserve protection and respect. If we lose them, we lose more than scientific

data. We lose pieces of our shared human history. We lose the soils that feed Kashmir's orchards and saffron fields. We lose the echoes of ancient earthquakes, the fossils of long-extinct species, the cultural artifacts of vanished communities. Protecting the Karewas means more than halting bulldozers. It means adopting thoughtful geoheritage management (Verma et al., 2023). Mapping important sites. Preserving exposures with unique sedimentary structures. Designing sustainable land-use practices that allow agriculture and development to coexist with conservation. It also means educating the public- telling the story of the Karewas so that local communities understand their value, not just as farmland, but as archives of time. If people can see them not as empty land, but as living history, they may feel the urge to protect them.

The Karewas of Kashmir are many things at once: geological archives, cultural repositories, fertile farmlands. They are memory keepers, storytellers, and life givers. But like all fragile things, they need



guardianship. Without protection, they will continue to vanish under the pressure of roads, rails, and concrete. And when they are gone, no science, no archaeology, no imagination will be able to bring them back.

So the next time you see a field of saffron blooming purple against the Himalayan backdrop, remember that beneath those flowers lie millions of years of history. Remember that every grain of soil there is part of a greater story-the story of Earth, of climate, of people, and of culture. The Karewas are Kashmir's forgotten tablelands. Forgotten, perhaps, by many- but not gone. Not yet. If we listen closely, their echoes still speak. The question is: will we answer?

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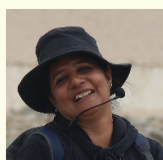
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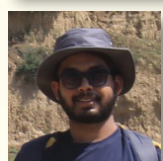
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About authors



Dr Binita Phartiyal, Scientist-F and Head of the Palaeomagnetism Laboratory, BSIP, Lucknow, has 28 years of research experience in Quaternary paleoclimate, geomorphology, and neotectonics. A geologist by training, she has led Himalayan (Tethyan and Trans-Himalayan) and participated in the Indian Scientific expeditions to Arctic and Antarctic.



Dr Shirish Verma is a geologist, specializing in Quaternary geology and palaeoclimatic reconstruction. His work provides critical insights into how high-altitude river and lake systems respond to global climate shifts, helping us better understand both past and modern environmental systems.



Dr Rakesh Chandra is Senior Professor at the Department of Geology, University of Kashmir, Union Territory of Kashmir, Srinagar, J&K, India, and working on geodynamics evolution of Indus Suture Zone and Shyok Suture Zone.

From Microscopes to Artificial Intelligence: How Technology is Transforming the Study of Microfossils

Anjali Trivedi, M.G. Thakkar and Anupam Nag

When Artificial Intelligence meets Earth's deep past

ARTIFICIAL Intelligence, or AI, has become one of the most discussed technologies of our time. It is influencing the way we communicate, travel, diagnose diseases, analyse satellite images and even predict weather patterns. But can the same technology help us understand something that existed thousands or millions of years ago? The answer is increasingly yes.

At the **Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow**, where scientists study the history of life, climate and environments preserved in the geological record, modern computational technologies offer an exciting new direction. One such possibility is the use of AI to automatically recognise microscopic fossils, particularly pollen, spores, phytoliths, diatoms etc. preserved in sediments.

At first, this may appear to be an unusual combination. AI belongs to the world of computers, algorithms and digital technology, while fossils belong to rocks, sediments, microscopes and Earth's ancient

history. Yet the two fields have something fundamental in common:

Both are concerned with recognising patterns

A scientist identifies a fossil by recognising patterns in its shape and surface. An AI system can also be trained to recognise patterns in images. This simple connection opens the door to a powerful new approach to palaeoscience. But before understanding how AI can recognise a fossil, it is important to understand what Artificial Intelligence actually means.

What is Artificial Intelligence?

AI is a broad term used for computer systems that can perform tasks that normally require some form of human intelligence. These tasks may include recognising objects, understanding language, finding patterns, making predictions and learning from information.

For example, when a smartphone recognises a person's face, when a navigation application predicts

How Artificial Intelligence, Machine Learning and digital imaging can help us read Earth's environmental history preserved in microscopic fossils

traffic or when a digital assistant understands a spoken question, AI is working behind the scenes.

AI does not necessarily mean that a computer "thinks" exactly like a human. Instead, it means that computers can be designed to perform specific intelligent tasks using data, mathematical methods and algorithms (Figure 1). One of the most important ideas within AI is **Machine Learning**.

What is Machine Learning?

Machine Learning, or ML, is a branch of AI in which computers learn patterns from data rather than being explicitly programmed with every rule.

Suppose we want a computer to distinguish between photographs of cats and dogs. Instead of writing thousands of rules describing every possible cat and dog, we can provide the computer with many labelled photographs. The system studies the examples and identifies patterns that help distinguish one group from another. After learning from these examples, the computer can examine a new photograph and make a prediction. This is the basic idea of machine learning (Figure 1).

The quality of the result depends heavily on the quality and quantity of the data used for training. If we provide the computer with a diverse and well-identified collection of examples, it has a better chance of recognising new examples correctly. This principle is highly relevant to microfossils.

What is Deep Learning?

Deep Learning, or DL, is a specialised part of ML. It uses structures called **neural networks**, which are inspired by the way networks of neurons process information in the human brain. DL systems can learn increasingly complex patterns from large amounts of data. For image recognition, this is particularly useful.

A DL model can gradually learn features, such as edges, shapes, textures and more complex structures from images. With sufficient training data, it can learn which combinations of visual features are associated

with particular objects. This makes DL particularly attractive for studying microscopic fossils.

A microfossil viz. pollen, spores, dinoflagellates, Phytoliths etc., may be only a few tens of micrometres in size, yet its outer surface can contain highly distinctive patterns. To a trained palaeontologist, these patterns can provide clues about the identity of the microfossil. To a computer, they can become patterns within a digital image.

From Deep Learning to Computer Vision

Another important term is **Computer Vision**. Computer Vision is the field of AI concerned with enabling computers to extract information from images and videos. It is already used in many everyday applications.

For example, computer vision can help autonomous vehicles detect roads and objects, assist medical professionals in analysing medical images and help satellites identify features on Earth's surface.

Now imagine applying the same principle to a microscope image. Instead of identifying a car, a person or a road, the computer is asked to identify a microfossil. Instead of analysing a satellite photograph of a forest, it analyses the microscopic architecture of a fossil. This is where AI begins to intersect directly with palaeoscience.

Why are microfossils important?

To understand the importance of automatic fossil recognition, we need to look at the fossils themselves. Microfossils, such as pollen and spores are excellent examples. Plants continuously produce pollen and spores, and many of these microscopic particles eventually settle on land, in lakes, wetlands and other environments. Their resistant outer walls allow some of them to survive burial and become preserved in sediments.

Over time, sediments accumulate layer by layer. Each layer can, therefore, contain a mixture of biological remains that reflects the surrounding environment at approximately that time. In this way, sediment can

act as a **natural archive of environmental change**. When scientists examine pollen preserved in different layers, they can reconstruct changes in vegetation through time. And vegetation is closely connected with climate.

The traditional microscope and the modern computer

For generations, scientists have used microscopes to study pollen and other microfossils. This requires considerable expertise. A researcher examines characteristics, such as the shape, size, openings and surface ornamentation of a pollen grain and compares them with reference material. Some pollen types are

relatively easy to identify. Others can be extremely difficult because closely related plants may produce pollen grains with similar characteristics. The problem becomes particularly significant when hundreds or thousands of grains have to be examined. A scientist may spend many hours at the microscope counting and identifying individual grains. The work is essential, but it is labour-intensive. This is where digital imaging and AI can provide assistance.

Teaching AI to recognise pollen

The basic concept is surprisingly intuitive. First, scientists create a collection of high-quality microscopic images whose identities are already known. These

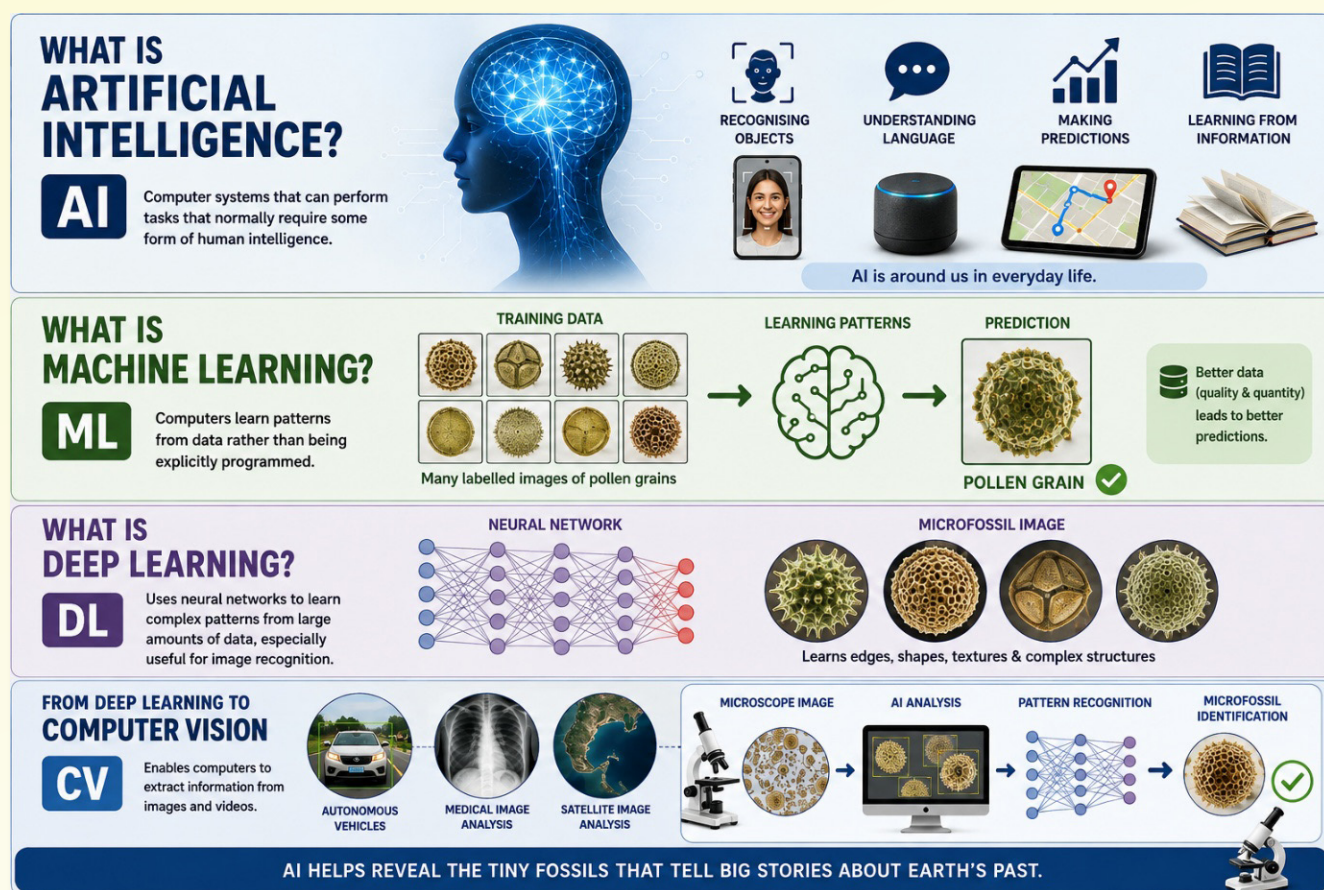


Figure 1. Conceptual workflow illustrating the progression from **Artificial Intelligence (AI)** → **Machine Learning (ML)** → **Deep Learning (DL)** → **Computer Vision (CV)**, and their application to **microfossil image analysis** and **pollen grain identification**.

images become the training material. The AI model studies the images and learns visual patterns associated with different pollen types. Once trained, the model can be given an image of an unknown microfossil. It then compares the visual characteristics of that image with patterns learned during training and produces a prediction.

For example, an AI model might be trained to distinguish between several common pollen types. The computer does not "know" what a tree or flower is in the same way a human does. It recognises mathematical patterns within the image. The scientist then evaluates the prediction. This is important. **AI should be considered an assistant, not a replacement for scientific expertise.**

The role of BSIP, Lucknow

This emerging approach has particular significance for the **Birbal Sahni Institute of Palaeosciences, Lucknow**. BSIP has a long-standing scientific legacy associated with palaeobotany, palaeosciences and the study of India's geological and biological past. The Institute is named after **Prof. Birbal Sahni (FRS)**, India's pioneering palaeobotanist, whose work helped establish the study of fossil plants as an important scientific discipline in the country.

The scientific questions have evolved considerably since the early days of palaeobotany. Today, researchers can combine traditional microscopy with digital imaging, geospatial information, statistical analysis,

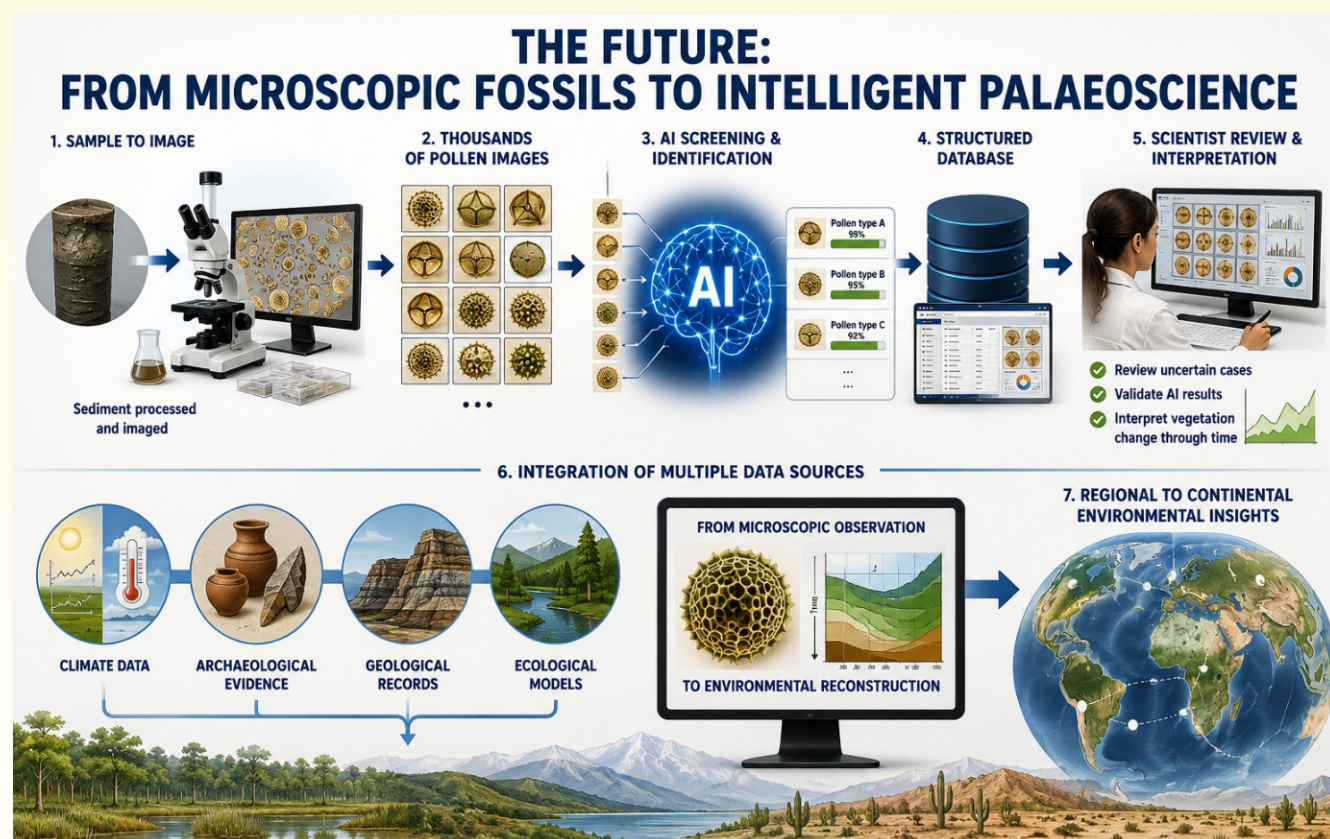


Figure 2. Conceptual framework for **AI-enabled palaeoscience**, showing the transformation of microscopic fossil observations—from sediment processing and digital pollen imaging to AI-assisted identification, database development and expert validation—and their integration with climate, archaeological, geological and ecological datasets to reconstruct environmental change from regional to continental scales.

databases and Artificial Intelligence. This does not replace the legacy of palaeoscience. Instead, it extends it. The microscope remains a window into the microscopic world. AI can become a new tool for opening that window at a much larger scale.

Creating India's First National Digital Repository of Microfossil Records

The development of AI-based fossil recognition also creates another exciting possibility: a comprehensive digital reference library. Imagine a digital repository containing high-quality images of pollen and spores from different regions of India. Each image could be connected with information about the plant that produced it, its geographical distribution, environmental preferences and other scientific characteristics. Such a repository could become a valuable resource for researchers, students and institutions. Over time, the collection could grow into a kind of **digital atlas of India's microscopic plant diversity**.

A new partnership between palaeoscience and technology

The integration of AI into microfossil research represents something larger than the adoption of a new computer technique. It represents a change in the way scientific information can be generated, stored and interpreted. Traditional palaeoscience gives us the specimens, knowledge and scientific questions. Digital imaging gives us high-quality visual records. Machine Learning provides pattern recognition. Deep Learning allows computers to learn complex visual features. Computer Vision allows these approaches to be applied directly to images and scientists provide the context, validation and interpretation. Together, these components create a powerful scientific partnership.

The future: from microscopic fossils to intelligent palaeoscience

Imagine a future laboratory at the intersection of palaeoscience and Artificial Intelligence. A sediment sample is processed and its microscopic contents are imaged digitally. Thousands of pollen grains are photographed. An AI system automatically screens the images and proposes identifications. The results are stored in a structured database. Scientists then examine uncertain cases, validate the AI results and interpret changes in vegetation through time (Figure 2).

The information can subsequently be combined with climate data, archaeological evidence, geological records and ecological models. Such a system could transform a microscopic observation into a regional environmental reconstruction. And if similar datasets are developed from different regions, scientists could begin to investigate environmental change across entire landscapes and continents. This is the promise of AI-enabled palaeoscience.

A new window into Earth's past

Artificial Intelligence is often presented as a technology of the future. Palaeoscience, on the other hand, is fundamentally concerned with the past. Bringing the two together creates an interesting paradox. ***The technology of the future can help us understand the world of the past and prepare for the world of tomorrow.*** A pollen grain may be only a few tens of micrometres across, but it can preserve evidence of forests, climate, monsoon behaviour, human activity and ecological change. For decades, scientists have patiently read these stories through microscopes.

Now AI offers a new way to assist them. The objective is not to replace the microscope or the scientist. It is to extend their capabilities to examine more specimens, build better databases, recognise

patterns more efficiently and connect microscopic evidence with larger environmental questions.

Institutions such as the Birbal Sahni Institute of Palaeosciences, where the history of life and Earth's changing environments is at the heart of scientific research, this convergence of palaeoscience and Artificial Intelligence offers an exciting new frontier.

The next generation of palaeoscience may, therefore, be neither purely microscopic nor purely

digital. It will be both. And perhaps, by teaching machines to recognise the smallest traces of ancient life, we will become better at understanding one of the biggest questions of our time: *How has Earth changed before, how is it changing now, and what might those changes mean for the future of life and society?*

About authors



Dr Anjali Trivedi is Scientist at BSIP, Lucknow. Her research focuses on Quaternary palaeovegetation and palaeoclimate reconstruction, including climate modelling and archaeobotanical investigations across different regions of the Indian subcontinent and South Asia.



Prof. MG Thakkar is the Director of BSIP, Lucknow. He is widely recognized for his pioneering contributions to Neotectonics, Palaeoseismology, Quaternary Geology, Geomorphology, Geoheritage and Geoarchaeology. His work has significantly advanced the understanding of landscape evolution, active faulting, and seismic hazards.



Mr Anupam Nag is Research Scholar at the BSIP, Lucknow. His research focuses on Quaternary palaeovegetation and palaeoclimate studies. Through these studies, he contributes to understanding long-term vegetation and climate variability and their relevance to future climate perspectives.

Exploring Ladakh as a Potential Martian / Lunar Analogue Research Station for Space Exploration in India

Dr Binita Phartiyal, Scientist F and Head, Palaeomagnetism Laboratory, Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, and General Secretary, XXII INQUA Congress, India 2027, in conversation with **Dr Nimish Kapoor**, Science Communicator and Scientist, BSIP, and Co-convener, SCoPE

Discusses the scientific significance and potential of Ladakh as a site for a Martian/Lunar Analogue Research Station in India. The conversation explores the unique geological and environmental characteristics of Ladakh, its relevance for planetary analogue studies, and the opportunities such a research station could offer for advancing interdisciplinary research in Earth and planetary sciences, as well as for preparing for future human exploration of the Moon and Mars.

As space exploration advances at an unprecedented pace, India's ambitious space programs are capturing the world's attention. With the Gaganyaan mission aiming to send Indian astronauts into space, plans for a space station, a mission to the Moon, and aspirations to land on Mars, India is pushing the boundaries of space exploration. To support these groundbreaking goals, there is a growing need for advanced testing grounds here on Earth that can simulate the extreme conditions of outer space.

One of the most promising locations for such research stations is Ladakh. Known for its breathtaking landscapes and harsh environments, Ladakh's geography closely resembles the surfaces of the Moon and Mars, making it an ideal site for conducting critical



Confluence of the Indus and Zaskar Rivers: A spectacular meeting point where the turquoise waters of the Zaskar River merge with the Indus, creating a striking natural landscape. The confluence reflects the region's dynamic geology and the powerful role of rivers in shaping the rugged terrain of Ladakh

scientific experiments, training astronauts, and fostering international collaboration in space research.

In this interview, we delve into the innovative proposal by Dr Binita Phartiyal, Dr Alope Kumar, and Dr Shubhanshu Shukla to establish a Martian/Lunar

analogue research station in Ladakh. Their research highlights how this unique region can play a pivotal role in advancing India's space exploration efforts while also benefiting local communities through tourism and outreach programs.

The Gaganyaan Programme, approved in December 2018, is at the forefront of India's space ambitions, with a focus on sending astronauts into Low Earth Orbit (LEO) and developing the critical technologies needed for long-duration human space missions. By 2035, the vision includes the creation of an operational Bharatiya Antariksh Station (BAS) and an Indian-crewed lunar mission by 2040. As part of this journey, ISRO, in collaboration with national agencies, academia, and industry, will run several critical missions to demonstrate and validate technologies that will lay the foundation for India's future space missions.

Through this interview, we aim to engage students, aspiring scientists, and the general public in an exciting conversation about how Ladakh's unique environment can contribute to global space research, the importance of analogue stations, and how India's space missions are shaping the future of space exploration.

Here are the excerpts from the interview.

Nimish Kapoor (NK): Why do you believe analogue research stations are crucial for the success of future human space missions?

Binita Phartiyal (BP): Because analogue research stations provide a critical bridge between Earth-based research and actual space missions, offering a way to test, refine, and prepare for the challenges of human space exploration.

NK: How does Ladakh's geography and climate make it an ideal location for simulating conditions on Mars and the Moon?

BP: Ladakh's geography and climate make it an excellent location for simulating the harsh and remote conditions found on Mars and the Moon due to several key factors namely extreme altitudes and rugged terrain; low temperature; arid and dry climate; isolation; above tree line; sparse vegetation, challenging terrain for mobility etc.

Hence Ladakh's unique combination of altitude, harsh climate, arid landscape, and isolation provides a natural "Earth analogue" for the extreme conditions astronauts would face on Mars and the Moon. As a result, it's an invaluable location for testing technologies, systems, and strategies in preparation for future human space missions to these distant worlds. The Ladakh sector has Hot springs (Chumathang, Panamik); Saline lakes (Tsomoriri, Pangong Tso, Toskar); glacial lakes (North Pulu, south Pulu, Tsoltak, Yaya Tso Mithpal Tso etc., where extreme environments can be studied with the focus to life in extreme environments.



Pangong Tso: A spectacular high-altitude lake in Ladakh, renowned for its striking blue waters and dramatic mountain surroundings. Its extreme altitude, cold climate and seasonal freezing make it an important natural analogue for studying harsh environments and planetary exploration



Frozen Pangong Tso: The iconic high-altitude lake of Ladakh partially transforms into a frozen expanse during winter, with ice covering its surface amid the stark, snow-clad Himalayan landscape

NK: What are some of the key scientific and engineering experiments that can be conducted in Ladakh to support space exploration?

BP: Several...Ladakh offers an exceptional environment for conducting scientific and engineering experiments to support space exploration, particularly due to its extreme conditions that mimic those on the Moon and Mars. Some key experiments that can be conducted in Ladakh to advance space exploration are-geological and resource exploration including analogue geological research.

Ladakh's arid environment offers a good testing ground for experiments in extracting resources from the environment, such as mining for water ice or processing regolith for building materials. These experiments will be critical for future lunar or Martian colonies, where resupply from Earth will be limited. Habitat and building materials testing can be done by seeing the durability of building materials and habitat

structure testing by making temporary habitats and inflatable modules can be tested to simulate conditions on Mars or the Moon.

In Ladakh a variety of rocks, igneous, sedimentary and metamorphic rocks are found. Robotic exploration and mobility by rover testing of Ladakh's rocky, uneven terrain provides an ideal landscape for testing autonomous rovers that will be used for lunar or Martian surface exploration and drones and aerial exploration as the high-altitude, low-atmosphere conditions of Ladakh offer an opportunity to test drones designed for atmospheric exploration on Mars or the Moon. Space suit and extravehicular activity (EVA) testing; energy generation and storage' communication and navigation systems, radiation protection are some other fields of experiments.

One of the important areas is the biological and psychological studies as in the harsh conditions of Ladakh, especially the low oxygen levels and physical isolation, allows scientists to study how the human body adapts to extreme environments. Research on acclimatization, endurance, and health during long-duration exposure to harsh environments can inform space mission planning. Ladakh's remoteness provides a real-world setting to study the psychological challenges of isolation and confinement that astronauts will face on deep-space missions. These studies help understand how prolonged isolation, limited social interaction, and distance from Earth can affect crew well-being and performance.

Hence Ladakh's extreme and isolated conditions provide a unique and invaluable environment for testing a wide range of scientific and engineering technologies that will be crucial for future space exploration missions. From life support systems and habitat construction to robotic exploration and astronaut performance, Ladakh serves as an ideal Earth analogue in India for simulating the challenges astronauts and researches will face on the Moon, Mars, and beyond.



Leh from Khardungla Road

NK: How can studying extremophiles in Ladakh's unique environment contribute to the search for life on Mars and the Moon? (Extremophiles are organisms that can live in very harsh environments, such as extreme heat, cold, or dryness, where most other life forms couldn't survive)

BP: Studying extremophiles in Ladakh's unique environment can significantly contribute to the search for life on Mars and the Moon in several ways. Ladakh's harsh and extreme conditions—such as low oxygen, freezing temperatures, high UV radiation, and dry, desert-like landscapes—closely mirror the environments on Mars and the Moon. Understanding how extremophiles thrive in such environments can offer critical insights into how life might exist or have existed on these other celestial bodies.

By studying extremophiles in Ladakh's extreme environment, scientists can gather valuable insights into how life could survive in similar conditions on Mars and the Moon. Understanding the biological mechanisms that allow these organisms to endure extreme cold, dryness, radiation, and low oxygen helps refine our search for life on other planets. Moreover, these studies can aid in developing detection techniques for microbial life, strategies for resource utilization, and approaches to human survival in space, making the study of extremophiles in Ladakh crucial to advancing astrobiology and space exploration.

NK: You mentioned that Ladakh's topography is similar to that of Mars and the Moon. Can you elaborate on some specific features that make it a strong analogue?

BP: Ladakh's topography offers several features that closely resemble the surface of Mars and the Moon, making it an excellent Earth analogue for space exploration. Some specific features include:

1. **Barren, Rocky Landscape:** Ladakh's rugged, rocky terrain with minimal vegetation mirrors the barren, rock-filled landscapes of Mars and the Moon, which lack substantial plant life or lush ecosystems.
2. **High Altitude and Low Oxygen:** The region's high altitude (up to 25,000 feet) simulates the low atmospheric pressure and reduced oxygen levels on Mars and the Moon, providing an environment that challenges human survival, much like the conditions astronauts would face on these bodies.
3. **Dry and Arid Climate:** Ladakh's extremely dry conditions, with little rainfall, mimic the water-scarce environments of Mars and the Moon. This makes it a good testing ground for resource management and survival strategies in places where water is either scarce or frozen.
4. **Harsh Temperature Extremes:** Ladakh experiences significant temperature fluctuations, from freezing cold in winter to warm summers.
5. **UV Radiation Exposure:** Ladakh's clear, high-altitude skies expose it to high levels of UV radiation, resembling the lack of atmosphere on the Moon and Mars, which both have no protective ozone layer to shield from solar radiation.
6. **Isolation:** The region's remoteness, with limited access to resources and infrastructure, parallels the isolation astronauts would experience on long-duration missions to Mars or lunar bases, helping researchers simulate human conditions in isolated environments.

These factors combined make Ladakh an ideal location for testing equipment, studying survival strategies, and understanding the challenges of living in environments like Mars and the Moon.



Folds in Ladakh: Intensely deformed and folded rock layers bear witness to the immense tectonic forces generated by the collision of the Indian and Eurasian plates, offering a glimpse into the geological evolution of the Himalaya

NK: Could you explain how such an analogue station would also benefit local communities in Ladakh, especially through tourism and outreach programs?

BP: By creating a space analogue research station in Ladakh, the region could experience significant benefits in terms of economic growth, job creation, and infrastructure development. The local communities would gain from increased tourism, new educational opportunities, and global recognition, while also being involved in innovative scientific advance-



Puga: A high-altitude geothermal region in Ladakh, known for its hot springs, sulphur-rich deposits and unique geothermal activity. The extreme environment and unusual geological features make Puga an important site for studying Earth processes and potential planetary analogues

ments. Additionally, the presence of the research station could foster greater environmental and cultural awareness, ensuring that both Ladakh's unique heritage and the advancement of space exploration go hand in hand.

NK: How can students and aspiring scientists get involved in this exciting area of space research?

BP: Students and aspiring scientists can get involved in the exciting world of space research by pursuing



Frozen Grounds of Ladakh: Permafrost and seasonally frozen ground in the high-altitude landscape of Ladakh, shaped by extremely low temperatures and prolonged winters. These frozen soils provide valuable insights into cold-region processes and serve as natural analogues for studying planetary environments

relevant education, participating in research and outreach programs, volunteering with space agencies or analogue stations, and building a network with professionals in the field. Whether through internships, citizen science, or direct participation in simulated space missions, there are numerous ways to engage with space exploration and contribute to the search for life and the future of human space missions. The opportunities are vast, and anyone with a passion for space science and exploration can take steps to make a meaningful impact.

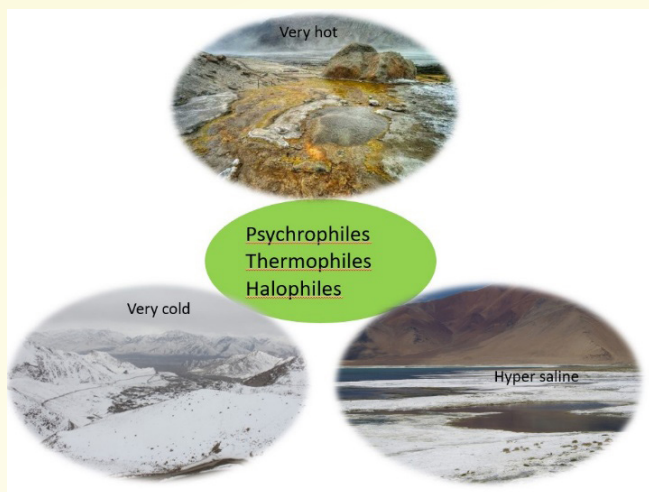
NK: Could you describe some of the early pilot projects conducted in Ladakh, like those done through NASA's Spaceward Bound India programme?

BP: The 2016 Spaceward Bound India expedition was an important early initiative that brought together scientists and researchers from India, the United States, Australia and other countries to explore Ladakh as a potential terrestrial analogue for planetary environments. The expedition involved a range of scientific, educational and outreach activities. Researchers investigated Ladakh's high-altitude extreme environments, including glacial passes, sand dunes, hot springs, saline lakes and permafrost regions, and examined their relevance to astrobiology and future off-Earth exploration.

Several pilot activities were also undertaken to test

scientific methods, instruments and protocols in these environments. These included regolith–landform mapping, comparative planetary studies, testing of the HABIT instrument prototype associated with the ExoMars mission, and life-detection assays in brines, periglacial ice-mud and permafrost melt-water. The expedition also provided an opportunity to engage students and local communities through hands-on science activities and discussions on astrobiology, while fostering collaboration among Indian and international research groups.

The experience demonstrated that Ladakh offers a remarkably diverse set of extreme environments within a relatively accessible region. More importantly, it helped establish a scientific foundation for considering Ladakh as a long-term planetary analogue research site and contributed to early discussions on developing an astrobiology research roadmap for India. These pioneering activities provided valuable experience that can now inform the vision for a dedicated Martian/Lunar analogue research station in the country.



Extreme Conditions in Ladakh: High altitude, extreme cold, intense solar radiation and arid terrain make Ladakh a remarkable natural analogue for studying life and human adaptation under harsh planetary conditions

NK: What are the challenges you foresee in setting up and maintaining a Martian/Lunar analogue station in such a remote and extreme environment like Ladakh?

BP: Establishing and sustaining a Martian/Lunar analogue station in Ladakh—a high-altitude, cold desert environment—presents numerous challenges. These include environmental extremes, logistical and infrastructural constraints, sustainability concerns, technical difficulties, and long-term maintenance hurdles. However, overcoming these challenges is the key to successfully building a functional analogue station. Once established, this facility would enable year-round scientific research, providing invaluable insights into planetary exploration and bridging the gap between the terrestrial and extra-terrestrial realms.

NK: How do you see a site like Ladakh shaping the future of space exploration in India?

BP: I strongly believe that Ladakh can play an important role in shaping India's future in space exploration, particularly in the development of planetary analogue



Tso Kar: A high-altitude salt lake in Ladakh, surrounded by barren mountains and vast arid plains. Its saline waters, seasonal wetlands and extreme climatic conditions make Tso Kar a significant site for studying high-altitude environments and Earth–planetary analogues

research. Its high-altitude, cold and arid environment, unique geology, rugged terrain and extreme climatic conditions offer several features that resemble aspects of the lunar and Martian environments. This makes Ladakh a natural laboratory for testing technologies, instruments, field protocols and human-performance strategies under conditions that simulate some of the challenges of planetary exploration.

A dedicated Martian/Lunar analogue research station in Ladakh could bring together scientists from Earth and planetary sciences, space science, geology, biology, engineering and medicine to conduct interdisciplinary research. It could also provide an important training ground for astronauts and researchers, while enabling the development and validation of instruments and technologies before they are deployed in actual space missions.

More importantly, such a facility would strengthen India's capacity to undertake indigenous planetary analogue research and contribute to international collaborations in astrobiology and planetary exploration. I see Ladakh not merely as a place that resembles another planet, but as a living laboratory where we can study Earth processes to better understand other worlds—and, in the process, prepare ourselves for the future of human exploration beyond Earth.

NK: You have conducted extensive palaeoscience studies in Ladakh. Could you briefly share some of your past research in the region and how it relates to your current study on Martian/Lunar analogues?

BP: My researches in the Trans and tethyan Himalaya are in Geomorphology, landscape characterization, reconstruction of Quaternary climates using sedimentary archives especially lake sediments. I have been working in Ladakh since 2000 and have published more than 50 research papers from Ladakh and have done my DSc, which was awarded in 2024. I have participated in the Scientific expeditions to both the Poles (Antarctica (2005-06) and Arctic (2008)) and led/participated several field Excursions in the

places with extreme environments:

- High Altitude Cold Arid Desert of Ladakh & Zaskar: 16 expeditions
- Lahaul-Spiti Region: 3 expeditions
- Schirmacher Oasis, Antarctica: 1 expedition
- Ny-Ålesund, Arctic: 1 expedition

In all these years sequentially we have been able to fill in the gap in research data, come up with important themes and research problems to work on and come up with exciting results. My team has made extensive contributions to Quaternary landscape evolution, climate reconstruction and demonstrated a profound commitment to understanding climate and geological processes. My leadership in field excursions, training of personnel, and supervision of PhD and Master's students highlights my role in fostering the next generation of researchers.



Earth and Space Exploration Programme 1 - Teaching Activity at Ladakh

The significant findings reported by me and my team ranges from geomorphological mapping in Ladakh to the reconstruction of palaeoclimate and tectonic activities. Our pioneering work on palaeolakes and sediment deformation structures is crucial for understanding the interplay between climate change and seismicity in the region, have given a clue for analogue studies for Mars. We have utilizing advanced tools

such as GIS for palaeolake studies, along with multi-proxy approaches in high-altitude glacial lake analyse. The identification of arid phases in the Holocene and insights into the impact of climate on trade routes and human activities enrich our understanding of the socio-ecological dynamics in this unique landscape. Moreover, my interest in astrogeology positions my research at the intersection of Earth and planetary sciences, offering a novel perspective on geological analogues for Mars. This interdisciplinary approach can provide valuable insights into both terrestrial and extraterrestrial environments.

In additions I have made efforts to highlight the importance of geoheritage and the necessity for its protection for future research and geotourism further reflect my commitment to sustainability and conservation. Overall, my contributions have significantly advanced our understanding of climatic and geological processes and hold potential for future research and practical applications in climate modeling and heritage preservation.

NK: Finally, looking ahead, what do you hope to achieve through this research in Ladakh, and how do you envision it contributing to the broader goals of space exploration and scientific discovery in India?

BP: By leveraging Ladakh's unique environment for space research, the goals are not only to advance our knowledge of space but also to contribute to India's growing presence in the global space community. The research carried out in this cold arid desert can di-

rectly support the next generation of space missions, particularly by simulating conditions on Mars and the Moon, enhancing the sustainability of human space exploration, and providing valuable insights into the search for life beyond Earth. Furthermore, it can promote scientific collaboration, inspire young minds, and help develop technologies that have both space applications and real-world benefits for Earth. Through these efforts, India can strengthen its leadership in space exploration, positioning itself at the forefront of global scientific discovery and technological innovation.

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About Interviewer



Dr Nimish Kapoor is a Scientist and Science Communicator at BSIP. He serves as Co-coordinator of SCoPE – Media Unit and is actively involved in science communication for public engagement and partnership activities.

PRITHVI 2026 concludes successfully, establishing India's First National Platform integrating Palaeoscience, Documentary Cinema and Science Communication

Swati Tripathi and Nimish Kapoor

The three-day **PRITHVI 2026 – The Palaeoscience Film Festival of India and National Dialogue on Earth Science Communication**, organised by the **Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow** during **23-25th July**, concluded successfully after bringing together leading scientists, filmmakers, journalists, educators, researchers, students and communication professionals from across India. As India's first national film festival dedicated exclusively to palaeosciences and Earth science communication, PRITHVI 2026 emerged as a

pioneering initiative demonstrating how documentary cinema can bridge scientific research and society.

Dr Nimish Kapoor, Festival Convenor, introduced the vision of PRITHVI 2026, highlighting the role of films and creative storytelling in making Earth science accessible to society. The festival was inaugurated on **23 July 2026** with the ceremonial lighting of the lamp and the release of the **Festival Book** and **Palaeoscience Today**, BSIP's popular science quarterly. Welcoming the gathering, **Prof. Mahesh G. Thakkar**, Director, BSIP and Festival Director, emphasised that effective science communication is



essential for addressing present-day environmental and climate challenges. He noted that documentary films provide one of the most powerful means of communicating the story of Earth's evolution, fossil records and past climate change to society while inspiring informed action for the future.

Delivering the inaugural address, **Prof. Raj Kumar Mittal**, Hon'ble Vice-Chancellor, Babasaheb Bhimrao Ambedkar University, described PRITHVI as much more than a film festival, calling it a movement to democratise scientific knowledge and strengthen collaboration between science, media and society. Distinguished speakers including **Dr. Mukesh Sharma**, former Director General, Films Division; **Mr. Mahesh Jha**, Head, DW Hindi, Deutsche Welle; **Ms. Sujata Mehta**, renowned theatre artist and actor; and **Dr. Shiv Kumar Sharma**, National Organising Secretary, Vigyan Bharati, highlighted the growing importance of documentary filmmaking, environmental journalism and creative communication in promoting scientific literacy. The inaugural session concluded with the screening of **"Fossil Memoirs – Episode 1."**

Throughout the festival, participants attended an extensive series of masterclasses by eminent filmmakers and media professionals. Sessions explored cinematic portrayals of legendary scientists, environmental journalism, documentary filmmaking, artificial intelligence in filmmaking, geotourism, science communication, and visual storytelling in extreme environments. Speakers including **Nandan Kudhyadi**, **Ashok Kumar (DW Hindi)**, **Dr. Mukesh Sharma**, **O. P. Srivastava**, **Subha Das Mollick**, **Rakesh Rao**, and **Prantick Santra** shared

practical experiences on transforming complex scientific research into compelling visual narratives for wider public engagement.

The festival also hosted thought-provoking panel discussions focusing on environmental journalism, science communication, media, cinema and public engagement with Earth sciences. Scientists, journalists, educators and filmmakers deliberated on strengthening collaborations between scientific institutions and media organizations to make Earth science research more accessible, reliable and impactful for society.

Over three days, audiences witnessed a rich collection of invited and competitive films covering climate change, biodiversity conservation, geoheritage, geotourism, palaeosciences, environmental sustainability and natural heritage. The festival featured documentary films, short films, animation films, geoheritage productions and student films from across India, highlighting innovative approaches to communicating scientific knowledge through cinema. Notably, BSIP's documentary **"Palaeoclimate to Present: Unravelling Assam's Environmental Mosaic,"** was also screened in the competitive short film category, showcasing Assam's remarkable environmental history, biodiversity and palaeoclimate through interdisciplinary scientific research.

Day 2 commenced with a masterclass, "Nationalist Scientists: Prof. Birbal Sahni and Acharya P. C. Ray – Cinematic Portraiture," by veteran science filmmaker Mr. Nandan Kudhyadi. He shared insights into portraying the lives and contributions of Indian scientists through documentary cinema. His acclaimed short film "Revolutionary in the Garb of a Scientist," based on the life and legacy of Acharya



Prafulla Chandra Ray, was screened, followed by selected excerpts from a documentary on Prof. Birbal Sahni, highlighting his pioneering contributions to Palaeosciences and Earth science research in India.

The festival concluded with a grand **Valedictory Session and PRITHVI 2026 Awards Ceremony** presided over by **Prof. M. G. Thakkar**, Director, BSIP and Festival Director, along with **Dr. Nimish Kapoor**, Festival Convenor. **Padma Shri Dr. Anil Rastogi**, eminent theatre artist, Bollywood actor and former Deputy Director, CSIR-CDRI, graced the occasion as Chief Guest, while **Mr. Brijesh Mishra**, Editor-in-Chief, Bharat Samachar, attended as Guest of Honour. Both dignitaries appreciated BSIP for creating a unique national platform integrating Earth sciences, cinema and science communication to inspire environmental awareness and scientific temper.

The **PRITHVI 2026 Awards** celebrated excellence in Earth science and environmental filmmaking across a wide range of competitive categories. **Pavazah**, directed by **Akanksha Sood Singh**, received the **PRITHVI Grand Prix Award**, while **Layers of Silence (The Karewas of Kashmir)** by **Er. Abdul Rashid Bhat** won the **Best Documentary Film Award**. **The Cave Within Me** by **Banyllashisha Wankhar** was honoured as **Best Short Film**; **The Last Seed** received the **Best Animation Film Award**; **Center for Climate Change Research (CCCR): Dedicated to Understanding Climate Change**, directed by **Shompa Das** and **Dr. Rahul Chand Reddy**, was recognised as the **Best Climate Change Film**; **Kadiya Dhro: Grand Canyon of India** by **Er. Ritesh Jain** won the **Best Geo-heritage and**

Geo-tourism Film Award; and **H₂O** by **Bikramjit Goswami** received the **Best Student Film Award**.

Special honours included the **Outstanding Scientific Content Award for 10 Years of the Winter Fog Experiment (WiFEX)** by **Dr. Sachin D. Ghude** and **Dr. Sandeep Wagh** (IITM, Pune); the **Public Engagement in Science Award** for **Arth Ganga** by **Pankaj Ramendu**; the **Excellence in Science Communication Award** for **The Dirty Sky** by **O. P. Srivastava**; and the **Festival Mention Award** for BSIP's documentary **Palaeoclimate to Present: Unravelling Assam's Environmental Mosaic**, directed by **Dr. Swati Tripathi** and **Ms. Arya Pandey**, recognizing its contribution to communicating palaeoclimate research, biodiversity conservation and environmental change through documentary cinema.

Other notable recognitions included **Best Director** for **The Last Leaf Knows** (by Amit Raj), **Best Script** for **Song of Daringbadi Hills**, **Best Cinematography** shared by **Blurred Boundaries: The Mishmi and the Forest** and **Pavazah**; **Best Graphics & Editing** for **Jurassic Bark – Plants of the Lost World** by **Dr. Mukesh Sharma**, **Best Sound Design** for **Pavazah**, **Best Storytelling** for **Roxburgh's Ark** by **Subha Das Mollick**, **Best Educational Impact** for **To Turn a Tide**; the **PRITHVI Jury Award** for **Couple for the Environment**; the **Special Jury Award** for **Ek Ped Maa Ke Naam**; the **Jury Special Mention** for **Coorg Before Coffee**; and the **Jury Recognition Award** for **Chinar Man: The Silent Planter**. Award certificates and trophies were presented to the winners





in recognition of their outstanding contributions to science communication through documentary filmmaking.

In his concluding remarks, **Prof. Mahesh G. Thakkar** stated that PRITHVI 2026 has successfully established itself as a pioneering national platform where science, cinema, media and communication converge to inspire innovation, interdisciplinary collaboration and meaningful public engagement with Earth sciences. Over three days, the festival

strengthened partnerships among scientists, filmmakers, journalists, educators and students while reaffirming the transformative power of documentary films in promoting environmental stewardship, scientific literacy and informed public participation for a sustainable future. The event concluded with a vote of thanks, presentation of awards, a group photograph of awardees and the National Anthem, marking the successful culmination of PRITHVI 2026.





BIRBAL SAHNI INSTITUTE OF PALAEOSCIENCES (BSIP)

An Autonomous Institute under the Department of Science & Technology, Govt. of India
53, University Road, Lucknow - 226007

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BSIP's Vision and Mission

Study of past life and climate—the drivers, impacts, and processes to provide models that are different in today's world to understand evolutionary processes and climate with special reference to climate change, palaeobiodiversity, palaeo-environment, past civilizations in order to increase the credibility of future environmental projections.

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Quarterly Popular Science Magazine of the BSIP, Lucknow

Palaeoscience Today is published every quarter in the month of March, June, September and December. The Editorial Board of *Palaeoscience Today* invites contributions for the forthcoming issues. The magazine serves as a platform to bring palaeoscience research closer to society, highlighting the wonders of Earth's ancient past and their relevance to our present and future.

We are especially looking for popular science articles that communicate palaeoscience in a simple, engaging, and story-like manner. Articles should avoid technical jargon and be written with a wide audience in mind, including college students, young learners, educators, and the science-curious public.

What We Are Looking For

- **Feature Articles (1000–1500 words):** Well-researched, narrative-style explorations of discoveries, methods, or themes in palaeoscience.
- **Research spotlight/Columns (700–900 words):** Thematic write-ups under recurring sections such as *Fossil Story*, *Digging Through Time*, or *Palaeoscience & Policy*.
- **Science Shorts (500–700 words):** Quick insights into recent findings, innovations, or ideas.
- **Interviews & Q&A:** Conversations with scientists, students, or educators.
- **Photo Essays / Infographics / Visual Features:** Image-led stories, timelines, or creative visualizations.
- **Student Corner:** Contributions from research scholars and college students with guidance from mentors.
- **Accolades:** Recognitions received during the said time
- **Meetings and Workshops**
- **Field Notes and Insights**
- **Research Shorts**

Suggested Themes

- Evolution of Earth
- Discoveries in Palaeosciences
- Geology and Climate: Earth's Changing Landscapes
- Stories from Fossils
- Ancient Climates, Modern Lessons
- Heritage Rocks: Geosites & Conservation
- Tech and Tools in Palaeoscience
- Meet the Scientist | Ask a Palaeoscientist

Author Guidelines

1. **Audience First:** Write for non-specialists. Avoid jargon; where unavoidable, explain in simple terms.
2. **Narrative Style:**
 - Begin with a strong hook (a question, fact, or anecdote).
 - Use storytelling, analogies, and real-world connections.
 - Keep paragraphs short and flow logical (Introduction → Main Idea → Relevance → Conclusion).
3. **Scientific Accuracy:** Ensure correctness of facts. Provide informal references or hyperlinks (no formal citations required).
4. **Tone and Language:** Conversational yet professional. Use active voice. Avoid overly academic style.
5. **Visuals:** Authors are encouraged to provide high-quality images, diagrams, or sketches (with proper captions and credits).
6. **Relevance:** Link the subject to education, environment, culture, or daily life. Highlight India's contributions wherever possible.
7. **Originality:** Only original and unpublished articles will be accepted. Plagiarism check will be applied.

Submission Details – Where to Send Your Contribution

- **Deadline:** One month before every publishing quarter.
- **Format:** MS Word (.docx), Times New Roman, 12 pt or Open Document Format (ODF)
- **Email submissions to:** palaeosciencetoday@bsip.res.in
- **Subject line:** *Submission – [Article Title] – [Author Name]*
- Along with the article, please include:
 - A short biodata (about 50 words)
 - A high-resolution author's photograph

For queries and collaboration, please contact:
palaeosciencetoday@bsip.res.in

Dr Nimish Kapoor
Coordinating Editor
Palaeoscience Today

