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CONTENTS

EDITOR'S COLUMN

The East African Rift System is an active intercontinental rift extending several kilometres in length, with widely distributed bimodal volcanic rocks. Ethiopia is an exceptional area to study the evolution of magmatism during continental rifting, from pre-rift continental flood basalts up to sea-floor-spreading basalts. In the Afar Depression and in the Main Ethiopian Rift, Miocene and Plio-Quaternary volcanism is located along the rift axis and is related either to fissural activity in the rift or to central vent-type eruptions in the north. The total thickness of the volcanic flows is estimated to be 2,100 m. The volcanic eruption was highest at the central part of the Ethiopian uplift and that most of the fissure vents were located at or around the Afar Rift Zone (Getaneh et al., 2021).

The fumarolic extrusion in the Danakil Depression was active during most parts of the Quaternary. The sulphide hot springs have given rise to large-scale sulphur encrustation in the Danakil Depression, along with huge piles of evaporites like gypsum, sylvite, and sodium chloride. The vivid yellow deposits are both a beautiful and hazardous feature of this landscape, offering a glimpse into the Earth's volatile nature (https://www.tourhq.com/article/danakil-depression-2).

The recent eruption of the so far dormant, Hayli Gubbi volcano on 23 November 2025 offers researchers a unique chance to study a volcano that had never been observed in action during recorded historical time. Just before the explosion, a small-scale earthquake rocked the area, which came as a signal that magma was tearing into the crust, wading its way to the surface. The Afar Rift, where Hayli Gubbi and its well-known neighbour Erta Ale are located, is a hotbed of tectonic jostling of horst and graben, but the recent event highlighted just how little is known about the quiet processes of these volcanoes.

The explosive nature of this volcanic eruption is likely due to the accumulation of gas-rich volatiles and pressure build-up that reached the breaking point, leading to a sudden spurt of ash and gases. In such cases, the fragmented magma (tephra) gets ejected instead of flowing lava. Such eruptions are often more deadly and disruptive. The eruption of volcanic ash from Hayli Gubbi, for instance, led to the cancellation of flights in the Yemen-Saudi-Oman sector. The strong eastward-moving winds carried the ash and gaseous matter from Ethiopia to Yemen, Oman, Rajasthan and Punjab in India, and even China by late 25 November. Ash might have fallen in parts of Rajasthan, though it was of insignificant volume.

It is not the first time that volcanic ash fell on the surface of Indian Territory. During the FS 1987-1990 ash beds dated 74 ka BP and belonging to the Toba Volcano, were recorded from Quaternary formations in the Vamsadhara River valley in Odisha, the Madhumati River of the Narmada basin, and Gundlakama, Jurreru, and Sagileru in Andhra Pradesh (Devara et al., 2021). The Young Toba Tuff is seen as sediments within Quaternary alluvium as 19-cm to 2-m-thick layers. "The Toba ash occurs extensively in the Indian subcontinent and marks a ca.

74,000-yr-old event. In the Bay of Bengal and Indian Ocean it is about 10 cm thick, whereas in several alluvial basins, it is usually 1-3 m thick. The latter occurs in a partly reworked state but as nearly chemically pure first-cycle sediments. The ash has a broad north westerly dispersal pattern. Samples of ash from the Indian subcontinent compare closely with the youngest (74,000 yr BP) Toba Tuff and the deep-sea Toba ash in bulk chemical composition, REE signature, and bubble-wall shard morphology" (Acharyya & Basu, 1993).

B. M. Faruque
Editor

Suggested reading:

Acharyya S. K. and Basu P. K. (1993) Toba Ash on the Indian Subcontinent and its Implication for the Correlation of late Pleistocene Alluvium, Quaternary Research, Vol. 40/1.

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MULTICOMPONENT DIFFUSION DURING THE HEATING OF A SHOCKED BASALT AND A QUARTZ POLYMORPH AT 1,400ºC AND VARIABLE RUN DURATIONS UNDER A REDUCING ENVIRONMENT- A PRELIMINARY REPORT

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ABSTRACT

This experimental study investigates multicomponent diffusion behaviour at the interface between basaltic impact melt rock and a natural α-quartz crystal at 1,400°C for variable run durations to simulate post-meteoritic impact thermal perturbations. Microprobe analyses across the quartz-basalt interface reveal prominent diffusion profiles for Ti, Mg, Fe, Na, Ca, Al, and K, while Si shows minimal self-diffusion. The iron oxide phase formed metallic spherules of variable sizes under a highly reducing condition along with abundant vesicles in the basaltic melt under supra-liquidus condition. The results suggest finite change in quartz composition due to elemental diffusion from basaltic impact melt at 1,400°C irrespective of run duration which may further constrain quartz-coesite conversion during hypervelocity impact event.

***Keywords**: Diffusion, shock melting, coesite, basalt, reducing environment, hypervelocity impact*

1. Introduction

Diffusion is a fondamental, temperature-dependent process in which atoms, ions, or molecules migrate from regions of higher concentration to lower concentration, operating across atomic lattices to macroscopic scales (e.g., Cherniak and Watson, 1997, 2001; Watson and Baxter, 2007; Zhang et al., 2010; Mueller et al., 2010). The term originates from the Latin verb "diffundere", meaning "to spread out". This phenomenon occurs across various phase boundaries, including solid-solid, solid-liquid/melt/gas, melt/liquid-gas, and gas-gas interfaces. Diffusion mechanisms can be classified into volume diffusion, grain-boundary diffusion, self-diffusion, tracer diffusion, and chemical diffusion. The first experimental study of diffusion in gases was conducted by Thomas Graham in 1833. Subsequently, Adolf Fick (1829-1901), a German physiologist, established the quantitative framework for diffusion by formulating the fundamental law of diffusion, now known as Fick's First Law:

$$J = -D(\partial C/\partial x)$$

Where, 'J' is the diffusive mass flux (a vector quantity), 'D' is the diffusion coefficient or diffusivity (with units of length^2/time), 'C' is the concentration of the diffusing component (expressed as mass, atoms, or moles per unit volume, e.g., kg/m^3, atoms/m^3, or mol/m^3), 'x' is the distance and $\partial C/\partial x$ is the concentration gradient (a vector). The negative sign indicates that diffusive flux moves from high to low concentration, i.e., in the direction opposite to the concentration gradient.

Elemental diffusion plays a fundamental role in the geological process and is widely applied in thermochronology, exhumation rate measurements, and cooling rate estimations (e.g., Zhang, 2010; Watson and Baxter, 2007; Mueller et al., 2010). The diffusion coefficient (D) is strongly dependent on the physical state of the medium and temperature regimes, for example, D is relatively high in gases (about 10^{-5} m^2/s in air at 300 K); intermediate in aqueous solutions (about 10^{-9} m^2/s in water at 300 K); lower in silicate melts (about 10^{-11} m^2/s at 1,600 K for divalent cations), and extremely low in minerals (about 10^{-17} m^2/s at 1600 K for divalent cations) (e.g., Chakraborty, 1990; Brady, 1995; Zhang,2010). Such variations suggest that mineral systems are generally resistant to chemical homogenization unless subjected to elevated thermal conditions.

In natural settings, humongous temperature-pressure perturbations are registered in domains having witnessed hypervelocity impacts, leading to elevated elemental diffusion and induce mineralogical transformations in the target rock system. The confirmation of terrestrial meteorite impact sites is made using diagnostic evidences of shock metamorphism (Pati and Reimold, 2007; French and Koeberl, 2010). Among these, the formation of high-pressure phases is particularly significant. Coesite, a metastable high-pressure polymorph of silica, was first identified in Coconino sandstone in Meteor Crater, Arizona (Chao et al., 1996). The natural occurrence of coesite helps to recognise existence of quartz-bearing geologic formations in meteorite impact craters, as evidence of shock pressure exceeding ~2-3 GPa. Since then, coesite has been widely used as a shock indicator phase related to impact events, although it also occurs in other rocks not related to impact, such as kimberlites and as inclusions within ultrahigh-pressure eclogites.

The Lonar crater, located in Buldhana district, Maharashtra, India (Lafond and Dietz, 1964; Nayak, 1972; Fredriksson et al., 1973), is one of the three confirmed meteorite impact structures in India. The other two confirmed impact structures are the Dhala impact structure in Shivpuri district, Madhya Pradesh (Pati, 2005; Pati et al., 2008), and Ramgarh impact structure in Baran district, Rajasthan (Crawford, 1972; Grieve et al., 1988; Kenkmann et al., 2020). Jaret et al. (2016) confirmed the presence of coesite in impact melt breccias at the Lonar crater, demonstrating that quartz, occurring as vesicle infill within the basaltic host, was transformed to coesite under shock pressure generated during the hypervelocity impact. However, their study did not address the thermal effects on quartz embedded within basaltic impact melt, leaving uncertainties regarding the subsequent thermal history and post-shock diffusion processes experienced by these minerals during the hypervelocity impact event.

The present study aims to addresses the gap in our understanding of multicomponent diffusion behaviour between secondary quartz embedded within basaltic melt under supra-liquidus conditions. High-temperature experiments were conducted using natural

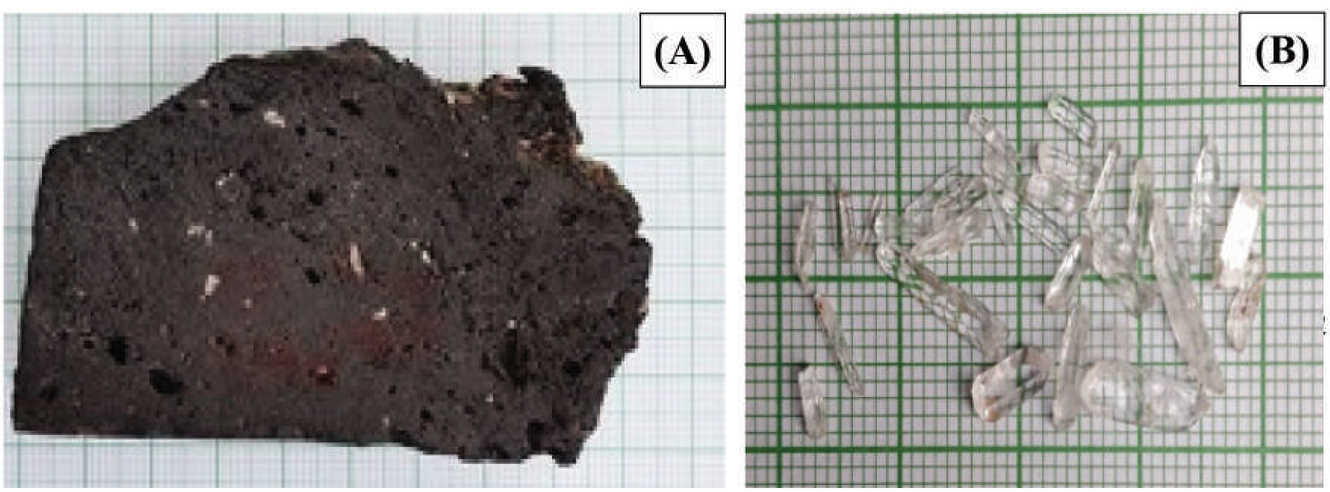


Figure 1: Starting materials used for experiments: (A) A slice of vesicular impact melt rock from the Lonar crater. (B) Crystals of quartz of varied sizes.

α-quartz crystals and Lonar impact melt rock (Figs. 1A and B), under a controlled oxygen fugacity environment and variable run durations, using a novel experimental setup (Fig. 2) to simulate post-shock thermal conditions. The results of this study provide new insights into the formation and evolution of compositionally zoned quartz-basalt interfaces. In particular, the development of compositionally uniform diffusion zones indicates limited temperature gradients during equilibration, and the observed tonal contrast at the crystal-melt boundary offers direct physical evidence of elemental diffusion mechanism operating during impact melt crystallization.

EXPERIMENTAL METHODOLOGY

A vesicular Lonar impact melt rock and natural quartz crystals of varying lengths (4-6 mm) and diameters (2-3 mm) were selected for the experimental study (Figs. 1A and B). The impact melt rock sample was dried in an oven at 100°C for about 30 minutes and then, crushed and grounded to fine powder in an agate mortar using acetone as a dispersant. The powdered material was subsequently heated at 100°C for 24 hours to ensure complete dehydration. The quartz needles were cleaned by immersing in concentrated hydrochloric acid for about 10 minutes, thoroughly rinsed with Millipore water, and dried overnight in an oven. The mineralogical compositions of starting materials were characterized by X-ray diffractometer (Pan Analytical, Germany) using Cu-Kα (1.5418Å) radiation and Ni filter at the National Centre of Experimental Mineralogy and Petrology (NCEMP), University of Allahabad. XRD scans were made between 10° and 75° (2θ scans) at a scan rate of 2° per minute using a generator voltage of 40 kV and a tube current of 30 mA.

The experiments were designed (Fig. 2) to be conducted under a reducing environment to preserve the valency states intact. For this purpose, two closely fitting graphite cylinders (inner and outer graphite cylinders/ crucible) were employed. The inner graphite cylinder was filled with powdered basalt, and a quartz crystal (L = 6 mm and D = 2 mm) was fixed vertically into the cap of the inner graphite cylinder, with the remaining segment protruding outward. This graphite cylinder was then inverted and placed into a large graphite cylinder/ crucible. The annular space between them was filled with graphite powder. This entire assembly was housed within a platinum crucible, with additional graphite powder added to maintain a highly reducing environment. The crucible assembly (Fig. 2), was positioned inside a molybdenum disilicide furnace at 1,400°C. The assembly was positioned close to the thermocouple as possible to ensure accurate uniform temperature exposure and minimal thermal gradients. Total four experimental runs were conducted at 1,400°C for durations of 15, 30, 45 and 60 minutes, respectively.

After each experiment, the run product was taken out and investigated under microscope at multiple magnifications to analyses textural and morphological features. The run products were further examined using

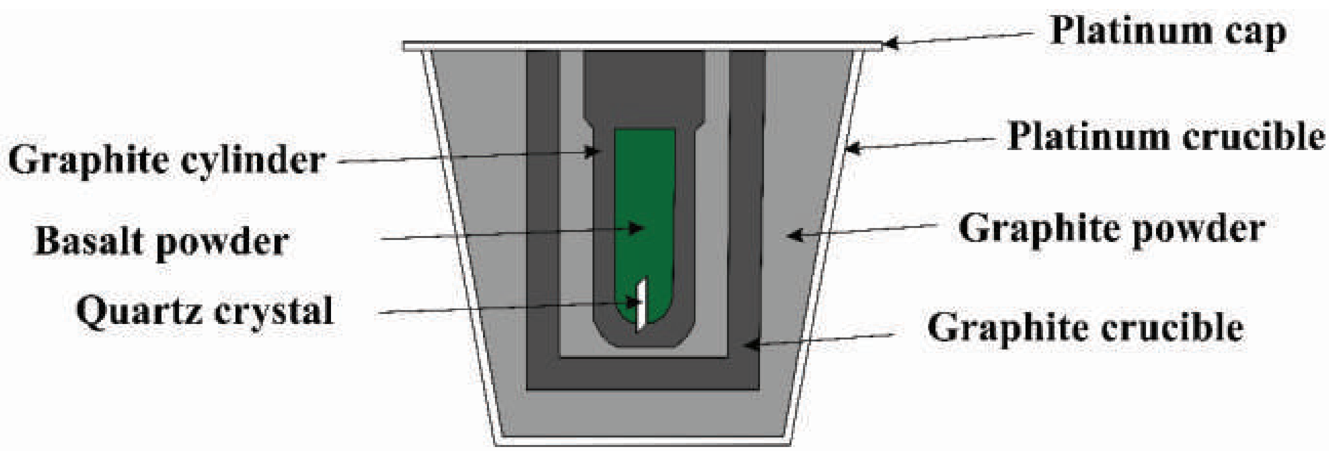


Figure 2: The schematic illustration of the experimental setups in a cross-section view (Figure not to the scale).

scanning electron microscopy (SEM) and electron probe microanalysis to characterize diffusion zones and elemental distribution profiles. Chemical profiling was performed using the electron probe microanalyzer (EPMA) at the National Centre for Experimental Mineralogy and Petrology (NCEMP), University of Allahabad. Scanning electron microscopy (SEM) was carried out to examine multicomponent diffusion and their gradients, including diffusion zones, if any.

RESULTS AND DISCUSSION

The XRD spectra of Lonar impact melt rock and quartz crystals are consistent with the mineralogical assemblages observed in thin-section under the petrological microscope. The present study complements the observations of Jaret et al. (2016) regarding coesite formation in the Lonar impact melt breccias. While their study primarily focused on pressure-related phase transformations during shock loading, the present study highlights the role of thermal effects and elemental diffusion in modifying the chemical composition of quartz-basalt (mineral-melt) interfaces during and/or post-impact events. The natural Lonar basalt and SiO_2 (Quartz) measure liquidus temperatures of ~1,150°C and 1,713°C under atmospheric pressure, respectively. Hence, a temperature of 1,400°C was chosen to better simulate the diffusion rate under post-impact thermal conditions and facilitate observable compositional changes over laboratory timescales. The elevated temperature also promotes silicate-metal immiscibility under strongly reducing conditions, effectively imposing oxygen fugacity near the iron-wüstite (IW) buffer. These conditions simulate the transient high-temperature, low oxygen fugacity environment likely developed within the impact melt during the crater formation. Under such conditions, diffusion-driven chemical modification of quartz grains embedded in melt becomes a key mechanism possibly controlling post-shock mineralogical and textural evolution, which was ignored earlier.

Superheating of the experimental charges at 1,400°C resulted in the development of abundant vesicles within the melts (Figs. 3A and B), accompanied by hemispherical bubbles (Figs. 3C and D) and fractures within the quartz crystals (Figs. 4A and B). These cracks are characterized by curvilinear traces, variable widths, and multidirectional orientations, indicating the combined influence of thermal stress and potential phase transitions. The observed vesiculations (Figs. 3C and D) suggest that the impact melt was inherently either volatile-rich, or that carbon from the graphite capsules reacted with oxygen released due to reduction of iron oxide (to metallic iron) present in basaltic melt at high temperatures to form O_2 (oxygen), carbon dioxide (CO_2) and carbon monoxide (CO), which subsequently mixed with the basaltic melt.

Metallic spherules are formed in all experimental runs and occur as discrete globules separated from the silicate melt due to liquid immiscibility and surface-tension driven detachment under IW-buffer condition (Figs. 3C and D). These metallic and glassy spherules show variable sizes and exhibit irregular flow-related morphologies (Fig. 3C). In the 30-minute run, small metallic spheres are disseminated around the quartz crystal and predominantly adhered to the crystal boundary. In contrast, the 60-minute run produced larger metallic spheres located towards the margin of the graphite capsule walls. The evidence of coalescence is observed where multiple smaller spherules merge along the melt flow path, forming progressively larger spherules (Figs. 3C and D). The metal- and gas-forming reactions are as follows:

$$\mathbf{2Fe_2O_3 \rightarrow 4Fe + 3O_2\uparrow}$$
$$\mathbf{Fe_3O_4 \rightarrow 3Fe + 2O_2\uparrow}$$
$$\mathbf{C + O_2 \rightarrow CO_2\uparrow}$$
$$\mathbf{2C + O_2 \rightarrow 2CO\uparrow}$$

The SEM examination of the run products exhibited nearly uniform diffusion zones, distinguished by tonal contrast at the quartz-basalt interface (Figs. 4C and D). The continuity and uniformity of these zones indicate relatively consistent temperature distribution/minimal temperature gradient within the experimental assembly, suggesting that the quartz crystals experienced a relatively consistent temperature field during heating.

The observed tonal contrast provides direct visual evidence of elemental exchange across the quartz-basalt interface. Two run products (30- and 60-min durations) were selected for detailed quantitative compositional analysis using EPMA, employing both point and line analyses.

Line analyses were conducted using JEOL JXA-8,100 EPMA at 15 kV, 20 nA, 1 μm probe diameter and dwell time of 1,000 mS. We have measured the concentration of Na, Mg, Al, Si, K, Ca, Ti and Fe along a line across the diffusion interface of basaltic melt and quartz. Variation in elemental concentration for 30- and 60-min run is shown in Figs. 5A and 5B, respectively. In these figures x-axis shows the distance across diffusion interface and y-axis shows X-ray count (characteristic peak with background). The region highlighted as the "Zone of Diffusion" marks the interface where elemental concentrations change progressively, suggesting chemical exchange between two adjoining mineral or melt phases. The diffusion zone width (~10-15 μm) provides a measure of the extent of interdiffusion under the prevailing laboratory condition or impact-related thermal regime. Such diffusion profiles are significant for understanding elemental mobility, thermal history, and reaction kinetics during syn- to post-impact melting or metamorphic equilibration. Characteristic peaks used for measurement are given below (Table-1).

Table-1: Characteristic peaks of different elements used for line analyses

Sl. No.	Element	Crystal used	L-value for Kα line
1	Na	TAP	129.47
2	Mg	TAP	107.51
3	Al	TAP	90.66
4	Si	PET	228.27
5	K	PET	119.87
6	Ca	PET	107.60
7	Ti	PET	88.07
8	Fe	LIFH	134.71

The chemical line profiles (~51.5 μm length, 1 μm beam size) across the melt-quartz interface revealed variable elemental gradients. The decrease of Fe concentration in 60-minute run as compared to 30-min run is due to its reduction and creation of large metallic spherules. In 60-minute run the zig-zag pattern for Fe is mainly due to X-ray background (Continuum X-ray). Elements such as, Ti, Fe, Al, Ca, Mg, K and Na show measurable diffusion from the basaltic melt into quartz (Figs. 5A and B). In contrast, Si displays similar but lower diffusion behaviour, suggesting variable diffusion of elements under identical experimental conditions. The Si^{+4} (0.40Å, in tetrahedral coordination) substitutes in varied amount for Ti^{+4} (0.42Å), Al^{+3} (0.39 Å) and Fe^{+3} (0.49 Å, in high spin state) in igneous environments. However, the self-diffusion of Si^{+4} is relatively slower than Ti^{+4} (Cherniak, 2003) but overall elemental diffusion is dependent on oxygen fugacity. The natural quartz crystal was placed vertically to monitor the elemental diffusion, along and across c-axis. Although, no significant variation was observed in igneous environments. This study further advocates that shock-induced thermal perturbations can significantly alter elemental diffusion gradients at mineral-melt interface.

There are variations in concentration of major elements at two different points in each, basaltic melt, quartz and metal spherule (Table-2). The concentration of Si increases toward the quartz side of the interface, reflecting uphill diffusion under the influence of chemical potential gradient (Figs. 5A and B). The basaltic impact melt is comparatively SiO_2-enriched compared to iron-rich spherules. Most of the iron from the melt segregated to form the metallic spherules under reducing condition and therefore, the diffusion of Fe in quartz exhibits a gentle slope, indicating a wider diffusion zone. Mg and Ca profiles show gradually decreasing slopes toward quartz, implying enhanced diffusion and a wider diffusion zone for both elements. On the other side, Al and K exhibit steep gradients at the interface, indicating minimal diffusion into the quartz crystal. Notably, Al_2O_3 is present in melt, but not in spherules, reflecting its retention in the silicate fraction.

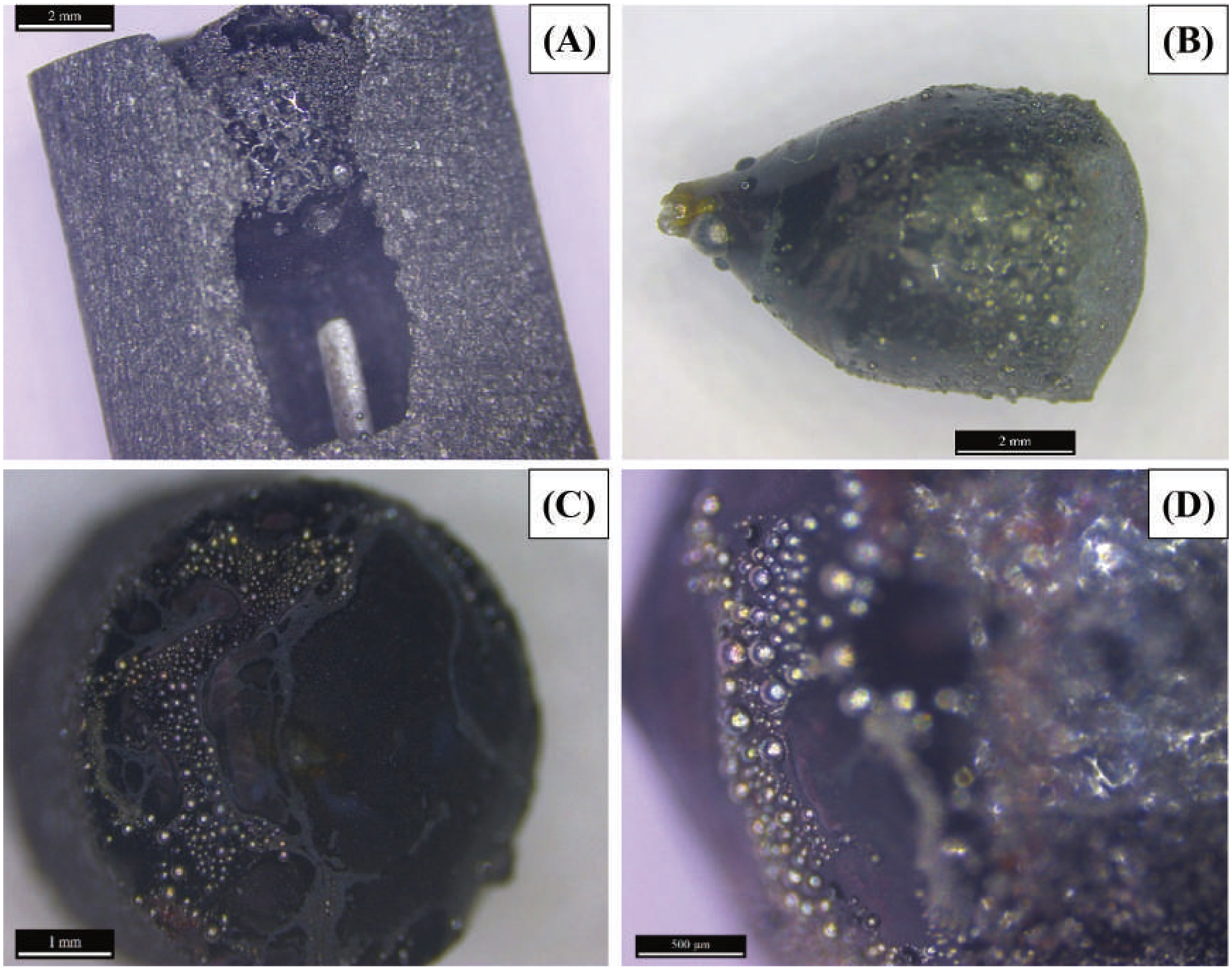
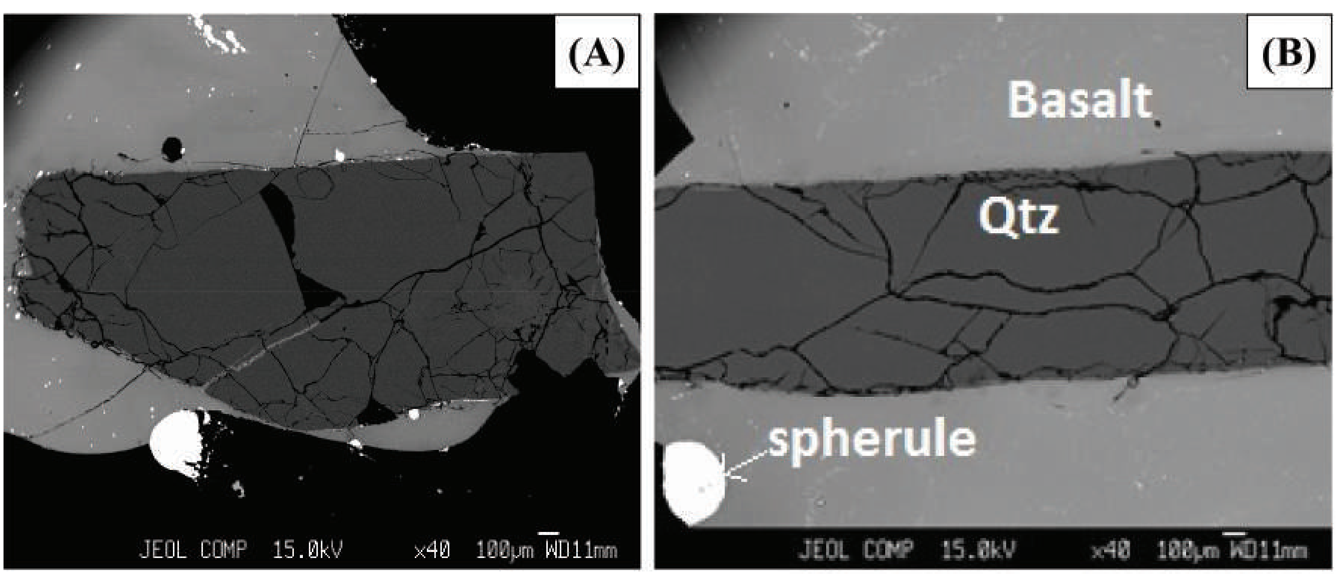


Figure 3: Photomicrographs of experimental run products performed at variable run durations of 30 (A) and 60 (B) minutes, respectively. (C-D) Spherules of varying sizes are spread within the basaltic melt, with trails of Fe-rich metallic droplets exhibiting an irregular, flow-controlled distribution pattern.



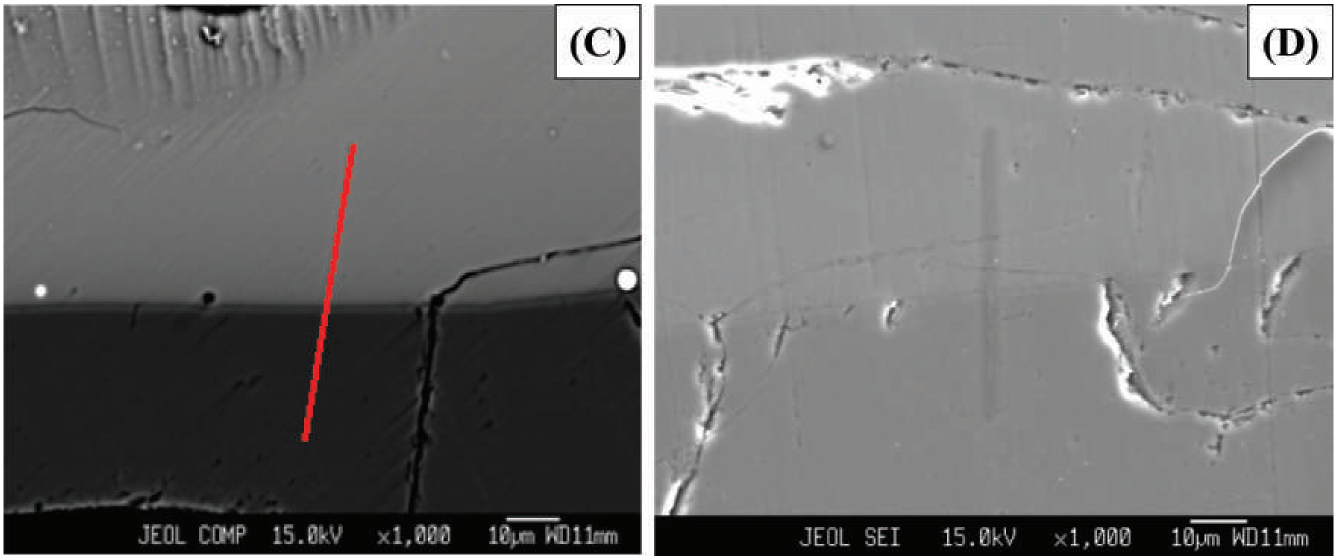


Figure 4: Backscattered electron (BSE) compositional images of run products corresponding to varied experimental run durations. (A-B) The image shows a highly fractured quartz grain (dark grey) resulting from thermal effects. The surrounding light-grey regions represent basaltic melt, while bright white circular features correspond to Fe-rich spherules. Iron-rich spherules are preferentially accumulated in the quartz-basaltic melt interface (A). Dark grey areas (A) indicate the graphite substrate. (C-D) Backscattered electron (BSE) images of the experimental run products showing compositional contrast between quartz (dark grey) and basaltic impact melt (light grey). Arbitrary line transects (red and grey colour, respectively) indicate locations where elemental concentration profiles were recorded across the diffusion interface.

Table-2: Chemical analysis of experimental run products

Element	Basaltic Melt Point 1	Melt Point 2	Quartz Point 1	Quartz Point 2	Spherule Point 1	Spherule Point 2
Na_2O	2.505	2.461	0.042	-	-	-
MgO	5.998	5.878	-	-	-	0.019
Al_2O_3	14.967	15.067	0.089	0.052	-	-
SiO_2	55.700	56.278	100.313	98.977	0.940	2.315
P_2O_5	0.065	0.057	0.026	-	11.854	3.601
K_2O	0.704	0.745	-	0.011	-	0.021
CaO	12.056	11.83	0.019	-	-	-
TiO_2	2.807	2.772	-	-	-	-
V_2O_3	0.032	0.060	0.024	0.011	0.165	0.073
MnO	0.205	0.180	-	-	0.020	0.023
FeO	3.618	3.565	0.035	0.002	98.28	93.092
CuO	0.041	-	0.014	-	0.153	2.043
Total	**98.698**	**98.860**	**100.562**	**99.053**	**98.2842**	**97.352**

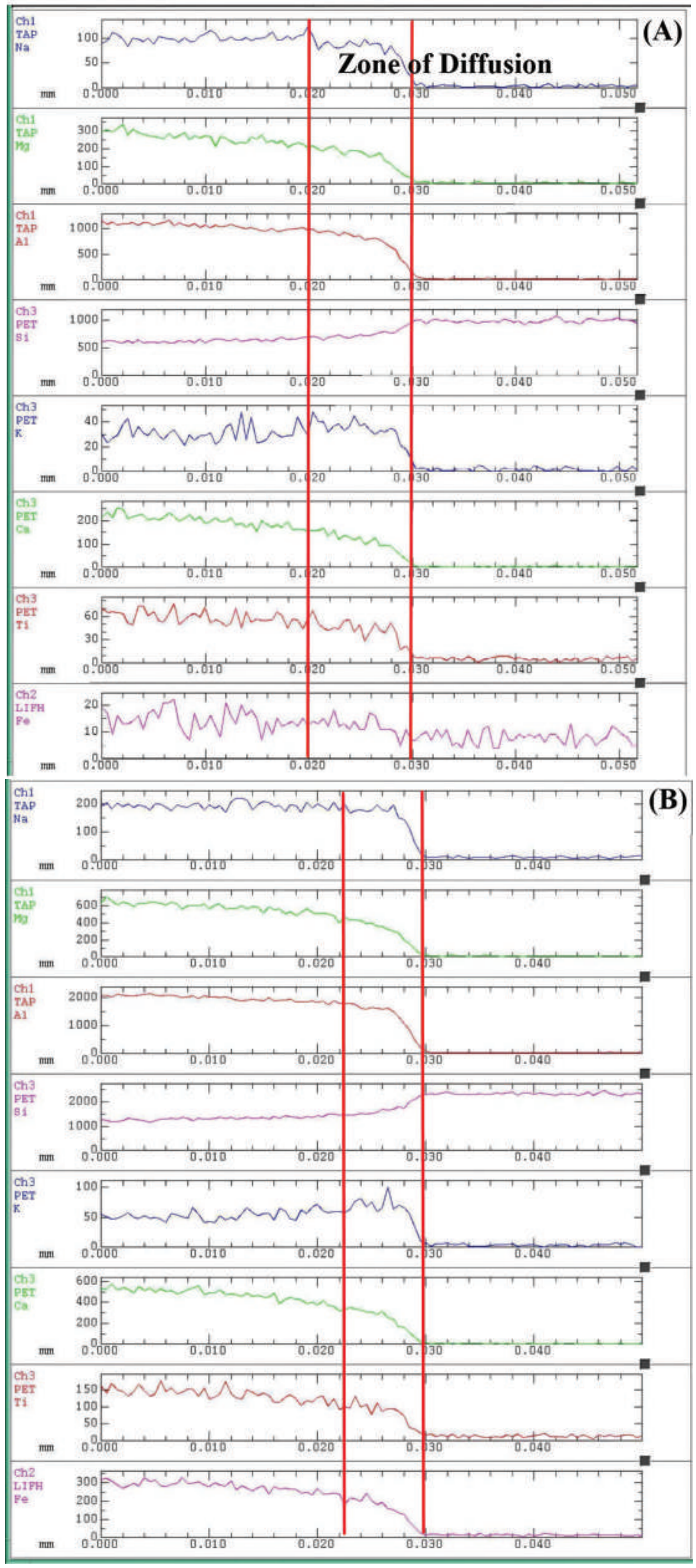


Figure 5: (A and B) Elemental spectra (Line analysis) acquired along these transects for run durations of 60 minutes and 30 minutes, respectively, illustrating compositional gradients across the diffused zone.

CONCLUSIONS

The elemental diffusion is a ubiquitous phenomenon in high temperature mineral and rock systems. However, theoretical and experimental studies are nearly absent to gauge such reactions during hypervelocity impacts under extreme temperature and pressure conditions. The present study is an attempt to understand the role of superheating pertaining to multicomponent diffusion in mineral-melt systems during the syn- and post-bolide impact stages under a highly reducing condition.

Observations of our experimental study demonstrate that elemental diffusion at the quartz-basalt interface under reducing conditions at 1,400°C results in: (i) uniform diffusion zones barring the interface domain indicating consistent temperature gradients, (ii) differential elemental mobility, with Ti, Fe, Mg, Na, Ca, Al, and K showing prominent diffusion, while Si self-diffusion remains low, (iii) formation of metallic spheres and vesicles, suggest volatile exsolution from the melt under redox condition, (iv) physical evidence of diffusion through tonal contrast changes is evident in BSE/SEM images, and (v) most importantly, post-experimental runs, the composition of natural quartz crystal has undergone change.

These results enhance our understanding of elemental redistribution within terrestrial impact structures, particularly in basaltic targets like the Lonar crater. The experimental methodology provides a foundation for future studies on impact-driven diffusion processes and their relevance to shock metamorphism and planetary geology. However, additional experiments are needed to further investigate these mechanisms and to better constrain complex pressure-temperature-time trajectories that remain challenging to replicate under laboratory conditions.

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A NEW COPPER PROSPECT NEAR KACHARAJAPALLY IN NALGONDA DISTRICT, TELANGANA

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Former Directors, Geological Survey of India

ABSTRACT

A new copper-gold prospect has been identified near Kacharajupally in Nalgonda district, Telangana. The studies conducted in the area clearly revealed this to be an ancient mining site. It is evident from the nature of openings (adits?) of the caves, which are made at three levels with an elevation difference of 10 m between them. The entire area has a thick malachite coating with patches of azurite. The mineralization is associated with the N-S trending quartz reef extending for more than a kilometre cutting across the granite gneiss of Peninsular Gneissic Complex and Srisailam Quartzite. The mineralization can be traced for 1 km long stretch having maximum width of 30 m. The samples collected from here analyzed to contain copper (Cu) ranging from 2.8 to 4.0 %.

Key words: *Caves, Srisailam Quartzite, Copper mineralization*

Introduction

This contribution reports a new copper-gold prospect occurring near Kacharajupally in Neredugomma Mandal of Nalgonda district, Telangana. Recently, local villagers have come across existence of two ancient cave like features located very close to west of Nagarjunasagar backwaters and Dindi rivulet near Kacharajupally. These caves are about 15 metre radii at the entry point, but the size narrows down inside. One of the twin caves is about 50 feet deep and the other is about 200 feet. This has come to the knowledge of the authors when the BIG TV team approached the first author with the photographs of the site and took an interview to know the technical aspects of the colourful caves. Instant look at the photographs revealed that the caves were not natural, but may have been developed due to ancient mining activity. The cave walls are thickly coated with malachite green and patches of azurite blue. Later, the authors made a visit to the site and confirmed this to be an ancient mining site. Additionally, sample were collected and analyzed and reported here for the first time.

Regional Geology

The study area is located in parts of Survey of India Toposheet No. 56 P/2 in the Eastern Dharwar

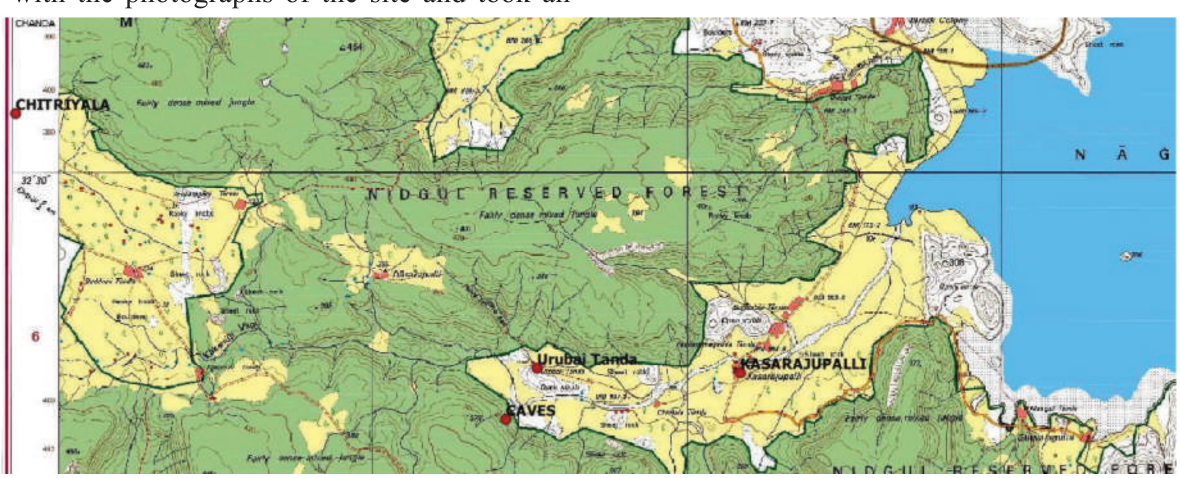

Fig. 1: Part of Toposheet no. 56P/2 showing location of caves in red circle.

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Craton, and exposes rocks belonging to Archaean to Paleoproterozoic Peninsular Gneissic Complex (PGC) & Mesoproterozoic Cuddapah Supergroup. The Granite Gneisses and other granitoids of PGC are overlain by the Mesoproterozoic sedimentary lithounits of Cuddapah Supergroup such as quartzite with the lenticular bands of limestone, dolomite, thinly bedded shale, slate and phyllites of Cumbum Formation and Srisailam Quartzite. Besides these, Neoproterozoic Kurnool Group of rocks represented by Banaganapalli, Conglomerate & Quartzite, Narji Limestone, Owk Shale and Paniam Quartzite are also observed. These lithounits are further intruded by basic dolerite/ gabbro and acid quartz reefs/ veins.

Fig. 2: Location of Kacharajupally Colourful Caves with evidences of copper mineralization in Google Imagery

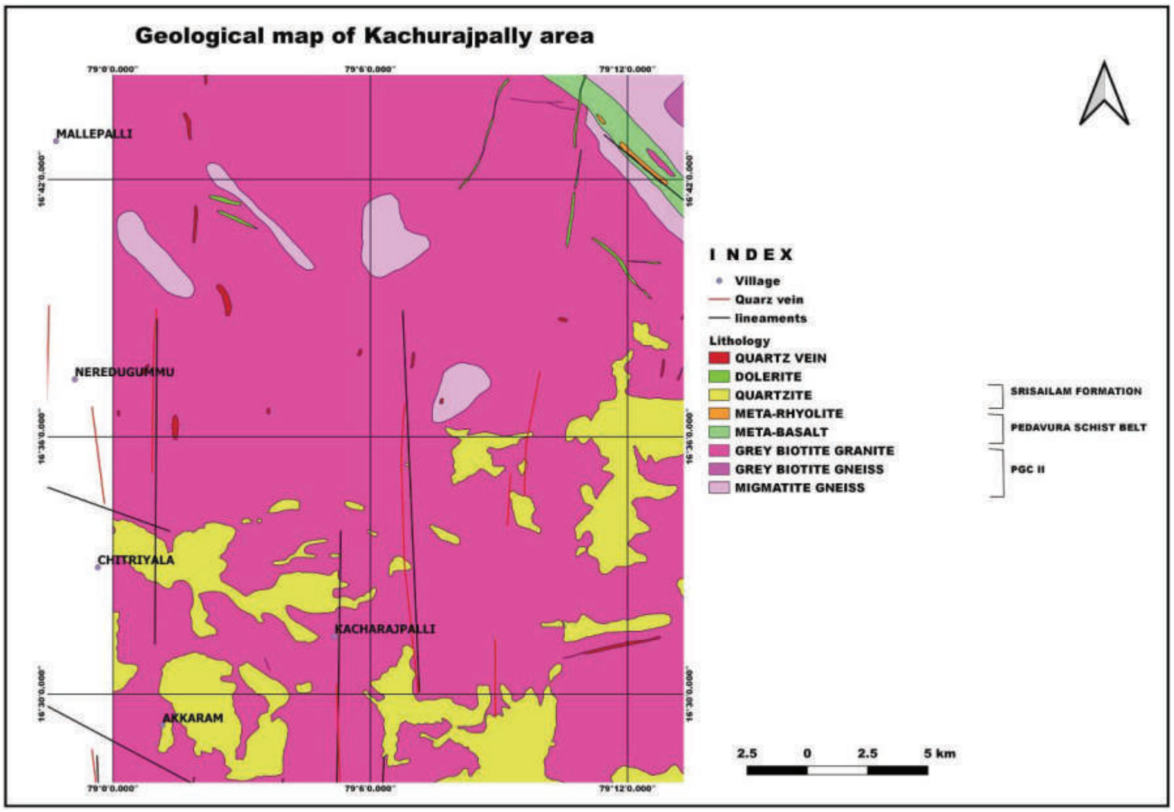

Fig. 3: Geological Map of Part of Toposheet no. 56 P/2 showing disposition of lineaments and quartz reef in the area (After GSI)

Mineralization

The mineralization near Kacharajupally is found to be hosted in a N-S trending quartz reef extending for more than two kilometers (Fig. 4a & b). The mineralized quartz reef cuts across the granite gneiss and quartzite. The quartz reef has got emplaced along the N-S fracture system. The mineralization characterised by alteration and associated with malachite & azurite is observed for about one kilometer. The width of this zone is about 30 m. The available evidences suggest that during ancient times openings/ adits for mining were made at three levels in the hill with elevation difference of about 10 m between them, which now appears like caves.

Four grab samples were collected from the mineralized zone and chemically analyzed by ICP-OES at Lucid Laboratories Pvt. Ltd. at Hyderabad. Three samples have yielded copper (cu) values raging between 2% to 4%, Pb from 57 to 2026 ppm. Zn from 37 to 77 ppm, and U from 38 to 200 ppm. The 4th sample analyzed slightly less copper (0.82 %), but Pb value increased to 2026 ppm. Besides these, these samples also gave gold (Au) values between 1.40 ppm to 5.50 ppm, silver (Ag) 1.56 ppm to 3.90 ppm, palladium (Pd) 3.94 ppm to 6.92 ppm. The values of gold, silver and PGE need further confirmation by more sensitive and accurate instrument like ICP-MS.

Fig. 4 (a & b): N-S trending quartz reef hosting copper mineralization and having old working openings at two different levels

Fig. 5 (a & b): Old workings in the quartz reef near Kacharajupally. Note the walls of the opening with profuse malachite coating

The preliminary study carried out clearly indicates it to be a potential copper-gold prospect with significant values of associated elements such as Ag, Pd, Pb, Zn and may turn out to be a polymetallic deposit. The analytical results and the geological setup suggest that this zone should be investigated in detail.

The local villagers and the State Tourism Department are showing interest to develop the site for tourism since it is located very close to Nagarjunasagar.

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THE RESTLESS EARTH

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ABSTRACT

"Dynamicity" or Restlessness is a universal and intrinsic property of all gross matters and processes. Earth, with a differentiated structure of Core, Mantle and Crust and its astronomical wobbling, is considered to be a typical case of restless body. While the restlessness of the Earth continues to raise its head even in present era by way of catastrophe and natural disasters, restlessness and technological stress of modern Man is viewed as an inherited property from the parent planet.

Key words: *Restlessness, Core, Mantle and Crust, Primitive and Modern Man*

INTRODUCTION

Restlessness (RLN) is an intrinsic property of the universe, reaching its pinnacle with the Big Bang 14.08 billion years ago. All processes - such as energy - mass conversion, the movement of electrons around a nucleus or planets around the Sun, the rushing of cosmic matter into black holes, plate tectonics, the evolution and sustenance of life, the stampede of pilgrims in places of worship, and the modern "rat race" in every field of life - generate restlessness. In short, creation is a product of restlessness in all gross bodies and the entire gamut of processes occurring on Earth.

For geologists and allied technologists, the story of the restless Earth begins 4.5 billion years ago when the planet formed through gravitational condensation of cosmic dust or cooling of peripheral solar material during pervasive cosmic movement. For a hind vision of the Earth, geologists, who are expected to supply the energy and mineral requirements of society, must understand the relative abundance (or possible abundance; Rankama et al., 1958) of basic constituents (Table-1) and their geochemical pooling (Table-2). Therefore, information on the geochemistry of meteorites may appear theoretical, but the abundance of different types - iderites, siderolites, or aerolites - indicates what minerals and metals are likely to be present in the Earth's interior, and in what forms: native (siderophile), sulphides (chalcophile), oxides and silicates (oxyphile or lithophile), sulphates (sulphophile), hydrophile, biophile, or atmophile. Subsequent processes that differentiated the basic constituents over a long geological period resulted in a layered Earth - Core, Mantle, and Crust - including the biosphere, hydrosphere, and atmosphere (Fig. 1).

Table-1: Abundance of Elements (Rankama et al., 1958)

Cosmic Abundance			Planetary Abundance			
	*Milky Way(%)	*Solar System (ppm)		Crust(%)	Mantle(%)	Core(%)
H	73.97	909964	O	46.1	44.3	-
He	24.02	98714	Si	28.2	21.3	-
O	1.04	774	Al	8.2	2.29	-
C	0,46	326	Fe	5.6	6.32	88.8

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Ne	0.13	100	Ca	4.1	2,48	-
Fe	0.11	27	Na	2.3	-	-
N	0.1	102	Mg	2.3	23.3	-
Si	0.07	30	K	2.0	-	-
Mg	0.06	28	Ti	0.5	-	-
S	0.04	16	H	0.4	-	-
			Ni	-	0.19	5.8
			S	-	-	4.5
			Others	0.5	-	<1

* Arnett, David (1996)

Table-2: Geochemical characters of elements (Goldschmidt, 1954)

Atmophile	Gas loving, or in compounds of Gas, volatile: N, O, C, Ar, Ne, He, Kr, Re, Rn
Biophile	A variety of elements associated with Organic life: C, H, N,S, P, Fe, O etc.
Hydrophile	H, O
Lithophile/Oxyphile	Rock loving: Ca, Mg, Fe, Mn, Ti, Na, K, U, Th, concentrated in Silicate rocks.
Chalcophile	Sulphur loving, affinity to S: Cu, Pb, Zn, Cd, Hg, Sb, Sn, Ag, Th, Te
Siderophile	Iron loving: Strong affinity to metallic Iron. Au, Ni, Fe, Pt, Mo, concentrated in Core.

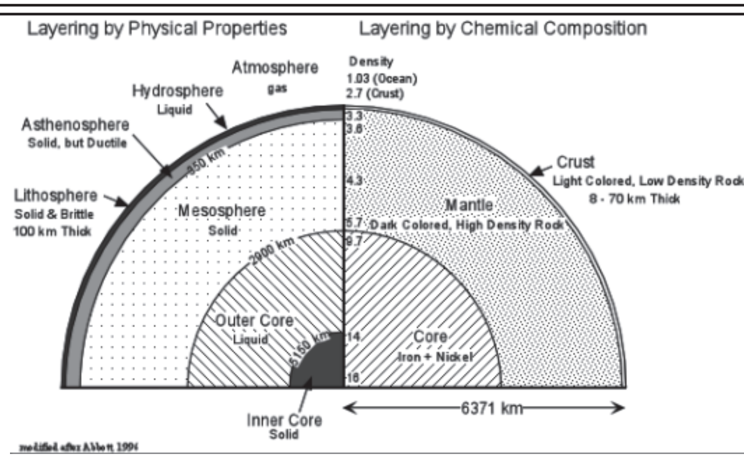

Fig.1: Earth has layered structure.

Layering can be viewed in two different ways

Compositional Layering

- ***Crust*** **-** variable thickness and composition
  - Continental 10 - 70 km thick - "granitic" (made mostly of Oxygen and Silicon) in composition
  - Oceanic 2 - 10 km thick - "basaltic" (less Silicon than in continental crust, more Magnesium)
- ***Mantle*** - 3,488 km thick, made up of a rock called peridotite. Solid (moves in response to temperature differences).
- ***Core*** - 2,883 km radius, made up of Iron (Fe) and small amount of Nickel (Ni)

Layers of Differing Physical Properties (Stephen A Nelson, 2015)

Lithosphere - about 100 km thick (deeper beneath continents)

- ***Asthenosphere*** - about 250 km thick to depth of 350 km - solid rock, but soft and flows easily.
- ***Mesosphere*** - about 2,500 km thick, solid rock, but still capable of flowing.
- ***Outer Core*** - 2,250 km thick, Fe and Ni, liquid
- ***Inner core*** - 1,230 km radius, Fe and Ni, solid

All of the above are known from observations that have been made from the surface of the Earth, in particular, the way seismic (earthquake waves) pass through the Earth.

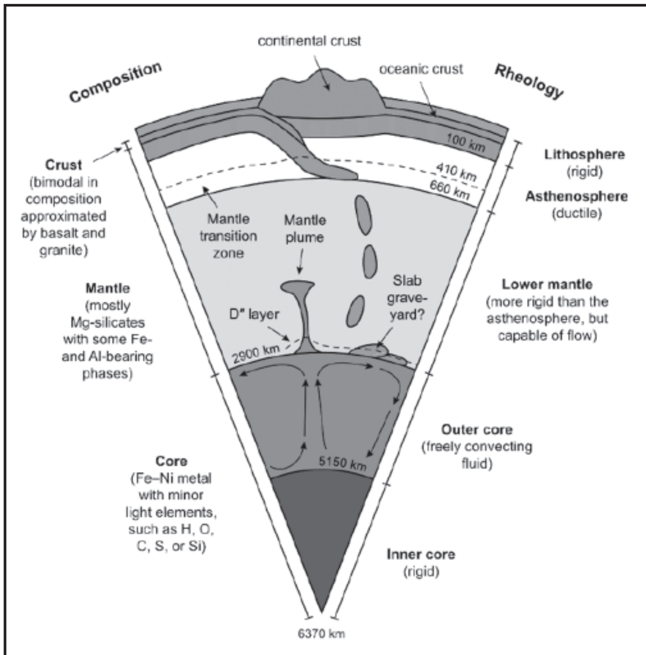

Fig. 2: Schematic diagram of Core, Active Mantle (With Asthenosphere) and Lithospheric Crust of Earth (Richard Palin, 2020)

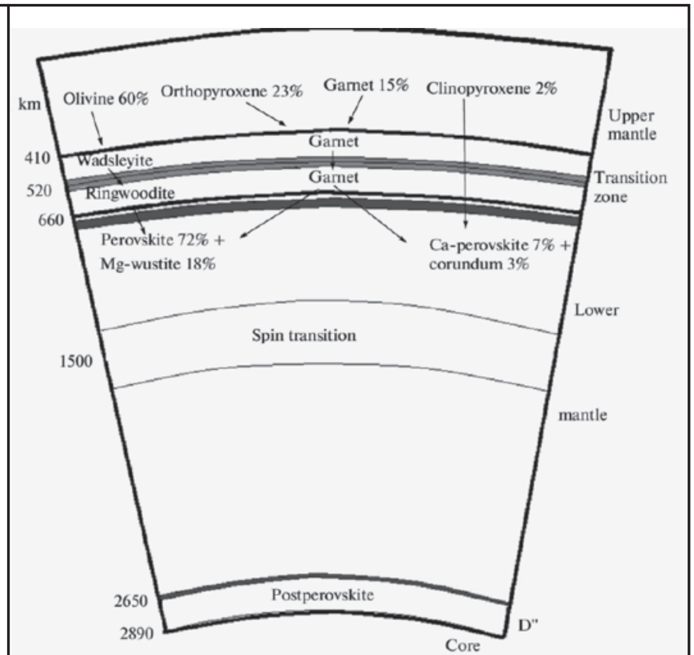

Fig. 3: Mineralogy with Index Garnets of the Mantle layers (Valeriy Petrovich, 2010)

The Wobbling Earth is Restless

The most significant and observable traits of the planet Earth are its astronomical position and its rotation and revolution around the Sun. The position of the Earth in the Goldilocks belt - not too near the Sun to be burnt out, not too far away in freezing cold - keeps the planet habitable with unique materials like water and "living things". Similarly, the diurnal rotation continuously maintains an equitable temperature and prevents the monotony of a permanent day or permanent night, which would mean boiling hot or freezing cold conditions over half the globe. Little do we realise that the entire creation and our existence on Earth are held safely, and not thrown into abysmal space, due to this diurnal rotation at about 1,500 km/hr. Gratefully, our scripture compliments the Earth as *Dharitri*, which holds us like a mother monkey with her baby tucked under the breast and jumping from tree to tree in search of cosmic foraging.

The "Pole Flucht Kraft" of Wegener (Herman Engelhardt, 2017), a centrifugal force that moves the plates, plays a role in creating the variety of geomorphic forms on Earth. The benefits of revolution around the Sun cannot be underestimated: without it we would lack comfortable and colourful seasons like autumn and spring, the bounty and blessing of rains and grains, and an equitable annual quota of solar energy irrespective of living in the northern or southern hemisphere. The last but not the least, wobbling of the Earth is precessional gyration, now known to result in the waxing and waning of solar radiation in every 41,000-year cycle, known as the Milankovitch Cycle, which produced natural global warming during Earth's geological history. In short, the grandeurs of existence on Earth are due to the restlessness of the wobbling planet.

Restlessness from the Evolution of Earth's Structure

As the planet cooled into a massive ball of 6,300 km radius, differentiated elements and their primitive compounds formed a layered structure akin to the skeleton of a gigantic organism - Gaia (James Lovelock, 1995). Iron, the most abundant element with a high melting point (1,530°C), separated by 'liquid immiscibility' and sank to the centre, forming the Core. Nickel, its geochemical companion, joined this differentiation, creating a 5,000 km ball of Fe–Ni alloy. Tremendous pressure transformed the inner core (about 2,500 km diameter) into a solid mass, while the upper part remained fluid and convective as the Outer Core (Fig. 1).

Eons of rotation produce slip between the inner and outer cores, generating Earth's magnetic field. Cooling increases the solid core at about one millimetre per year, reducing slip and gradually weakening the magnetic field - this relocates magnetic poles and may, in geologic time, become hazardous for life because the field shields Earth from energetic cosmic radiation. It also guides migratory birds, and changes may disrupt their migration and breeding.

Beyond the core lies a 2,900 km thick layer of femic silicates equivalent to oceanic basalt - the Mantle. With temperatures from 4,000°C at its base to 700°C at the top, it constitutes 67% of Earth's mass and 84% of its volume. Index minerals such as olivine, garnet, and perovskite classify it into upper, middle, and lower mantle (Fig. 3). Though primarily solid, the mantle flows slowly geologically, driving plate tectonics (Fig. 2).

Increased concentrations of volatiles and mineralisers in the upper mantle enhance mobility (restlessness), generate new crusts, ridges and furrows and, with extreme differentiation, produce zones and pockets of accumulation of valuable mineral materials (Fig. 2).

The mantle, rich in femic minerals, is followed upward by a relatively thinner layer of lighter felsic minerals, known as the crust of the Earth. Geologists familiar with the basic principles of magmatic differentiation are aware of the formation of simatic and sialic layers of the crust. The simatic layer is oceanic basalt, found invariably on the ocean floor, and the sialic layer represented by granites and gneisses occurs in continental regions. Crustal thickness varies from 10 to 100 km, overlain by sediments such as sandstone, shale, limestone, and banded iron formations (BIF). A veneer of soil and a blanket of life-supporting gases complete the system. Water vapour condensed into the world's oceans, covering three-fourths of the surface, and together with other phases of water sustains the hydrological cycle.

A doyen of Indian geology once compared the Earth's structure to an egg (Brahmanda - the Big Egg), suggesting that the essential elements of the cosmic egg and Earth are fundamentally similar.

Geobiological History of a Restless Earth

Thermodynamic condensation into a layered structure did not end the Earth's turmoil; rather, the RLN-DNA transferred to the crust and manifested repeatedly throughout geological history as tectonism, volcanism, magmatism, metamorphism, sedimentation, weathering, climate-driven events and geobiological forms (Table-3).

Major geological markers of RLN include global orogenies - particularly vivid in the Precambrian - formation of the primitive ocean, evolution of the atmosphere and the Great Oxidation Event (GOE), cycles of marine transgression and regression, asteroid bombardments leading to rupture of the Palaeogene crust and flood basalt eruptions, breakup of Gondwana, rifting of plates, and the building of the Rockies-Andes and Alpine-Himalayan mountains over the last 4.5 billion. The turmoil continues even today in earthquakes, volcanism along the Pacific "Ring of Fire," and natural disasters.

Equally significant is the biological turmoil accompanying the evolution of life. Life likely began with water-the elixir fluid-whose molecular vibrations may have jump-started life-like behaviour in inert minerals or synthesised amino acids under lightning sparks (Cairns-Smith, 1987; Sahu, K. C., 2023; C. J. Avers, 1989). The emergence of the first cells-prokaryotic or eukaryotic-from azoic materials was a miracle of biogeochemical struggle.

Subsequent neonatal care through the change from an anoxic to an oxic environment during the Great Oxidising Event and the transformation from aqueous or marine realms to terrestrial environments of plant and animal kingdoms were “natural selection” processes of evolution requiring tremendous efforts by both the transformed species and the transforming agencies.

The “Cambrian Explosion” introduced hard parts on earlier cyanobacteria and stromatolites; amphibians jumped out of the aqueous kingdom; vertebrae developed; reptiles crawled; birds and insects flew; while plants added colour to the environment. Ultimately, under the shadow of the gigantic dinosaurs, the mammalian species crawled into the world and later appeared as apes and man. Each transformation in evolutionary change was a struggle for survival in the process of natural selection, compelling modification of forms and adaptation to the changing environment. Failure either led to reduction in population or extinction. Five such episodes of extinction are noted in the biological history of Earth, and the last hominid now faces a similar fate, struggling against Nature’s determined course of evolution, not knowing that the driving force of the sixth extinction is himself (Elizabeth Kolbert, 2015).

Table 3: Some Geobiological Indicators of Events and orms of the Rest-less Earth.

Phanerozoic 541 Ma to present	Cenozoic 66 Ma to Present	Anthropocene (Unofficial geological epoch ~1950)	Human activities have become a dominant planetary force, altering Earth’s geology, atmosphere, oceans, and biosphere on a scale comparable to major events in deep Earth history!
		Holocene	Climatic stability that enabled the flourishing of modern ecosystems leading to profound, human-driven changes to the Earth system.
		Pleistocene	Appearance of Modern humans (Homo Sapiens), Extinction of large Mammals and Birds (mega fauna). Last Ice Age.
		Pliocene	
		Miocene	
		Oligocene	
		Eocene	
		Paleocene	
	Mesozoic 252 to 66 Ma	Cretaceous	5th mass extinction around 66 ma caused ending of the non-avian dinosaurs, likely due to a large asteroid impact. First flowering plants, Placental Mammals.
		Jurassic	
			4th Extinction around 201.3 Ma opened ecological niches for dinosaurs, possibly triggered by massive volcanism.
		Triassic	Dinosaurs Emerge

	Paleozoic 541 to 252 Ma	Permian	3rd mass extinction around 252 million years ago, the most severe, known as “The Great Dying,” wiping out ~96% of marine species.Gondwana Coal belt
		Carboniferous	First Amphibian
		Devonian	2nd mass extinction around 372-359 Ma impacted tropical marine life, including reefs.First terrestrial plants and animals
		Silurian	
		Ordovician	1st mass extinction around 444 Ma caused by glaciation and sea-level drops, devastating shallow marine life.Primitive Fish
		Cambrian	First Shell animal
Precambrian 4.6 Ga to 5.41 Ma	Proterozoic 2.5 Ga to 541 Ma		Rise of oxygen and the evolution of complex eukaryotes and early animals (Ediacaran fauna).
	Archean4 to 2.5 BY		“Great Oxidation Event” (BIF-Iron Ores) Earliest oxygen production Earliest evidence of life Formation of Water
	Hadean 4.6 to 4 Ga		Formation of Crust and MoonOrigin of Solar System

However, less conspicuous and more visible turmoil is observed in the biological trend involving origin and evolution of life during the same period of time. Life could be imagined to have started with the creation of water, the elixir fluid, which itself has internal molecular vibration that enabled the water molecule either to kick start life like activities in the inert rock forming minerals or synthesised Amino acid with input of energy from a spark of natural lightening (Cairns Smith, 1987, Sahu K. C., 2023, C. J. Avers, 1989). Delivery of a cellular form of life (Pro- or Eu-Karyotic cell) from azoic elements ought to have been a miracle of biogeochemical struggle. Subsequent neonatal care through change of anoxic to oxic environment of Great Oxidising Event and transformation from aqueous or marine environment to terrestrial environment of plant and animal kingdoms are “Natural Selection” of evolution requiring tremendous efforts by the transformed species and transforming agencies. It was in the “Cambrian Explosion” that hard parts appeared on the earlier cynobacteria and Stromatolites, the amphibians jumped out of the aqueous kingdom, developed vertebra, reptiles crawled, birds and insects flew while plants added colour to the environment. Ultimately, under the shadow of the gigantic Dinosaurs the mammalian species crawled into the world and later appeared as Apes and Man. Every transformation in the evolutionary change was a struggle for survival in the process of Natural Selection compelling modification of forms and adoption to the changed environment. Failure to either, the concerned life form got reduced in population or decimated to extinction. Five such episodes of extinction have been noted in the biological history of Earth and the last hominid now faces a similar fate and struggling to fight against Nature's determined course of evolution, not knowing that the driving force of the Sixth Extinctionis himself (Elizabeth Kolbert, 2015).

The Fate of Man

The Homo sapiens, or modern humans, are known to have evolved in the African jungles some 200,000 years ago. Adverse climate, paucity of food, and drying water holes, lakes, and reservoirs forced the Hunter & Gatherer tribes to move into the adjacent Fertile Crescent, where they learnt to grow food instead of searching for it, settled down, and domesticated animals. A group moved towards Europe, interbred with a stouter clan of Neanderthals, but decimated them in due course. Another group spread to the East and North-East to Iran, India, Australia, China and after crossing the Bering Strait, then a land mass, spread over to the Americas (Fig. 4). Since their appearance in the early Pleistocene, modern humans have undergone the rigours of two Ice Ages.

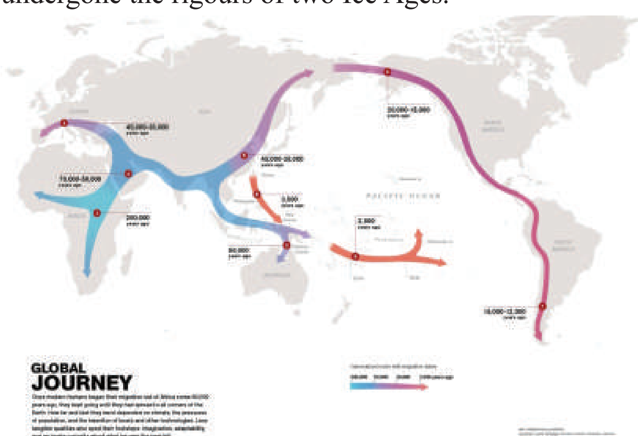

Fig. 4: Global migration and spread of Early Man (https://education.nationalgeographic.org/resource/global-human-journey/)

The global migration from tropical Africa to remote corners of Eurasia, Australia, and the Americas involved crossing deserts, snow-clad mountains, rivers, the Great Siberian Flats, and permafrost forests infested with prehistoric animals, often 50 to 100 times larger than themselves. This must have been a tremendous task, resulting in acute and chronic stress at both individual and societal levels. While on the move, some groups locally settled down and developed the well-known civilizations at Mesopotamia, Egypt, the Indus Valley, the Xia, Shang, and Zhou dynasties in China, and later the Greek and Roman Empires in Europe, as well as the Maya and Inca civilizations in the Americas. Some of these declined due to conflicting ethics, ideology, and religious beliefs.

During this long period of geographic spread, primitive humans went through a complex trajectory of modes of living, starting from hunting & gathering to agricultural subsistence, mercantile trade and commerce, industrial developments, and consumer capitalism (Simon & Mark, 2018). Each mode of living had its characteristic advantages, challenges, and rewards, but was beset with complex socioeconomic problems that visibly affected the behavioural patterns of humans. Therefore, during the same period, a lion remained a lion and a beetle remained a beetle, but primitive man with stick and stone became a globe-trotter brainiac with nukes, space ships, and robotic machines at his disposal.

Besides noticeable changes in behavioural patterns, scientists have noted significant enlargement in size and structural complexity of the brain, including changes in stature and gait. A progressive increase in cognitive capacity has evolved into a novel faculty of Science & Technology, empowering humans to master Nature and enabling them to bring about visible changes that Nature ordinarily takes millions of years to accomplish. For example, he could change the course of a river and flatten a mountain within a single generation. As such, annual generation and movement of erosional flux due to human activities now exceed that of Nature, and so also the capacity for using solar energy for photosynthesis and nitrogen fixation in agriculture. Man has turned out to be a greater change-maker and re-designer of Earth's morphology, not realizing that the consequences of his actions have profound effects downstream on his environment, way of life, and behavioural pattern.

The unstoppable power of Science & Technology, evolved from the faculty of cognition (Gnana), is not without a price for humanity. For example, the common piece of stone used by primitive humans as a handy tool after chipping and shaping became the primary material for building shelters and, in due course, palatial buildings, townships, and, from an artistic angle, majestic statues and sculptures-a sort of poetry in rock. The art of pottery and ceramics is also synonymous with the culture of stones. Cement and concrete aggregates manufactured from limestone and allied rocks now build all infrastructures, including roads and communication channels, and support urbanization and the spread of concrete jungles.

Similar to the use of stones, the discovery of fire as the primary source of energy, and later fossil fuel as the principal source of energy coupled with the invention of the Internal Combustion Engine (IC engine), laid the foundation of the Industrial Revolution and changed the quality and rate of progress of civilization. In both cases - use of stone or fossil fuel - the impact on the environment has been degrading and stressful.

Evolved as an offshoot of cognitive faculty, Science & Technology has helped banish hunger and malnutrition, eradicate endemic diseases, and make life more comfortable, but in the process has degraded the life-supporting systems - the air, water, and soil (food chain) - and made a trash of the Earth. The explosive bubble of cognitive capacity has also given rise to Artificial Intelligence and, with robots and machine language, has made man redundant. The large mismatch between biological and cultural evolution results in conflict and complex psychological problems (Reynolds, V., 1984). Information overload, technological stress, and fear of redundancy produce additional stress in life. The unstoppable desire for possession and power has made "brothers at arms," the home divided by narrow domestic walls with frequent conflicts, wars, and terrorism.

With all that said above, modern man is more restless than his primitive counterparts and appears to have inherited the RLN-DNA from the parent planet.

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UNDERSTANDING GLACIERS: FORMATION, CHANGE, AND THEIR IMPORTANCE IN A WARMING WORLD

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ABSTRACT

Glaciers are critical components of the Earth system, shaping landscapes, regulating hydrological regimes, and serving as sensitive indicators of climate change. In recent decades, rising temperatures, shifting precipitation patterns, and an increase in extreme events have accelerated glacier retreat across nearly all mountain regions. This manuscript synthesises current understanding of glacier formation, mass balance processes, and the climatic and geomorphic controls that govern glacier behaviour. It examines how rapid cryospheric change affects water availability, mountain hazards, ecosystems, and downstream societies, with a particular emphasis on regions that are undergoing heightened vulnerability due to limited monitoring and exposure to compound risks. The paper highlights advances in remote sensing, field observations, and modelling that have improved our ability to assess glacier evolution, track ice loss, and evaluate associated hazards such as avalanches, ice-rock collapses, debris-flow surges, and altered river flow regimes. Finally, the study highlights the importance of integrated monitoring, improved prediction tools, regional data sharing, and community-centred adaptation to manage glacier-related risks effectively. Strengthening scientific capacity and climate-resilient planning is essential to safeguard water resources, reduce hazard impacts, and enhance societal resilience in a rapidly warming world.

Keywords: *Glacier dynamics; Climate change; Cryosphere monitoring; Mountain hazards; Water resources*

Introduction

Glaciers are large, slow-moving bodies of ice that store freshwater, reshape mountain landscapes, and influence regional and global climate systems (Eshankulovna, 2025). Although they often exist in remote polar regions and high mountain ranges, their presence or absence affects the lives of hundreds of millions of people (Hock et al., 2019). Glaciers act as natural freshwater reservoirs, storing water as ice during cold periods and releasing it slowly as meltwater during warmer seasons (Shangguan et al., 2025). This seasonal pulse of water is vital for rivers that support agriculture, drinking water, hydropower, and ecosystems across the world. In many mountain regions, including the Himalaya, Andes, Alps, Rockies, and Central Asia, meltwater from glaciers sustains river flow during dry months when rainfall is minimal (Molden et al., 2021). In this way, glaciers quietly provide water security to entire nations. Beyond their role in water availability, glaciers serve as some of the clearest long-term records of Earth's climate (Hock and Huss, 2021). Their size, shape, and thickness reflect a delicate balance between temperature and snowfall. Even small changes in climate leave a noticeable imprint on glacier mass (Kulkarni et al., 2021). When temperatures rise, glaciers melt and retreat; when temperatures fall, they grow. Due to this sensitivity, glaciers are often referred to as "natural thermometers" (Thompson and Thompson, 2025). For over a century, scientists have monitored glaciers to track changes in the global climate system, and these long-term records consistently show accelerating glacier retreat in recent decades (Azam et al., 2021). However, glacier retreat is not just a scientific observation; it has real consequences for landscapes and communities

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(Pole, 2022). As glaciers shrink, they expose unstable slopes, deepen valleys, and uncover depressions that can rapidly fill with meltwater to form new glacial lakes (Pole, 2022; Ahmed, 2025). These changes increase the likelihood of landslides, rockfalls, debris flows and outburst floods (Sattar et al., 2025). Some of the most damaging disasters in mountain regions have occurred when water stored in newly formed lakes was released suddenly due to moraine failure, heavy rainfall, ice or rock avalanches, or the collapse of unstable slopes (Haeberli & Whiteman, 2021). As warming continues, these hazards are expected to intensify, particularly in regions where high population density, expanding infrastructure, and limited early warning systems heighten vulnerability (Wang et al., 2021).

On a global scale, glacier melt contributes significantly to sea-level rise (Durand et al., 2022). While the Greenland and Antarctic ice sheets contain the largest volumes of ice, mountain glaciers worldwide are melting at a rapid rate, making their combined contribution to sea-level rise comparable to that of the major ice sheets (Rigonet, 2022). This means that glacier loss in distant mountain ranges can ultimately reshape coastlines and affect communities thousands of kilometers away. Glaciers also possess deep cultural, ecological, and aesthetic significance (Salim et al., 2021). For many indigenous and mountain communities, glaciers are revered as sacred beings and central to their cultural identity (Dangles et al., 2025). For others, they represent wilderness, natural wonder, and a connection to the planet's high places (Salim et al., 2021; Malone et al., 2024). Ecologically, glaciers support unique habitats-cold-water streams, alpine wetlands, and specialised plants and animals adapted to extreme conditions. The disappearance of glaciers threatens not only water and landscapes, but also their cultural values and fragile ecosystems (Drenkhan et al., 2023). As climate change continues to accelerate, understanding glaciers has become more important than ever (Hock and Huss, 2021). They are not merely frozen masses of ice-they are dynamic systems that breathe with the seasons, regulate water flows, respond swiftly to environmental change, and act as powerful indicators of the planet's overall health (Spiridonov et al., 2025). Their transformation, now occurring across every glaciated region of the world, tells a broader story about our climate, our water resources, and our shared future (Molden et al., 2021).

In this article, we explore the fundamentals of glaciers, their formation and movement, their role in storing and releasing water, the methods used to study them, and the patterns and drivers of glacier retreat. We also discuss the implications of glacier loss for water resources, ecosystems, and communities, with a particular focus on the Himalayan region. By presenting these concepts in clear and accessible language, this article aims to deepen public understanding of glaciers and highlight the urgent need for monitoring, adaptation, and coordinated climate action.

2. How Glaciers Form and How They Move

Glaciers begin with something simple and familiar snow. In the high mountains or polar regions, temperatures remain so cold that the snowfall in winter does not completely melt by summer. When this process repeats year after year, the accumulated layers of snow grow thicker and heavier. Over time, the weight of the overlying layers compresses the older snow beneath, squeezing out air and transforming the snow first into dense, granular **firn**, and eventually into solid, crystalline **glacial ice**. This transformation can take decades to centuries, depending on the local climate. What begins as soft snow gradually becomes part of a massive, frozen body that can stretch for kilometers. Once a glacier is thick enough-typically more than 30-40 metres-the pressure at its base causes the ice to behave like a slow-moving fluid. Although glaciers appear rigid and immobile, glacial ice deforms under its own weight and begins to flow downslope (Jennings and Hambrey 2021). This movement is incredibly slow in most regions, typically progressing at a rate of just centimetres to a few meters per day, but in some cases, it can be significantly faster. Where a glacier rests on steep terrain or is lubricated by meltwater at the base, the entire ice body can slide more rapidly over the underlying rock. In rare cases, some glaciers experience **surges**, advancing several kilometres in a short period due to sudden changes in internal water pressure or ice deformation (Paul et al., 2021). Every glacier is divided into two primary functional zones. The upper accumulation zone is where snowfall exceeds melt, serving as the glacier's source of "income" as new snow compacts into ice. In contrast, the lower ablation zone experiences a net loss of ice through melting, sublimation, evaporation, or calving. The balance between these zones determines whether a glacier advances or retreats: when accumulation surpasses melt, the glacier grows, while dominant ablation causes it to shrink. The glacier's lowermost end, known as the terminus or snout, shifts position over time in response to these changes. Figure 1 illustrates the key components of a glacier system, showing the transition from accumulation to ablation and the role of the equilibrium line altitude (ELA), which divides these zones. The diagram also identifies major geomorphological features-including the snout, terminal and lateral moraines, and a proglacial lake with an outlet stream-demonstrating how glaciers interact with and shape the surrounding landscape under varying climatic conditions.

As glaciers move, they become powerful landscape sculptors. Their immense weight grinds underlying rock into fine sediment called glacial flour, carves deep U-shaped valleys, and drags boulders for great distances. Meltwater running on, though, and beneath the glacier forms networks of channels and contributes to river flow downstream. In monsoon-influenced or temperate mountain regions, meltwater stored under the

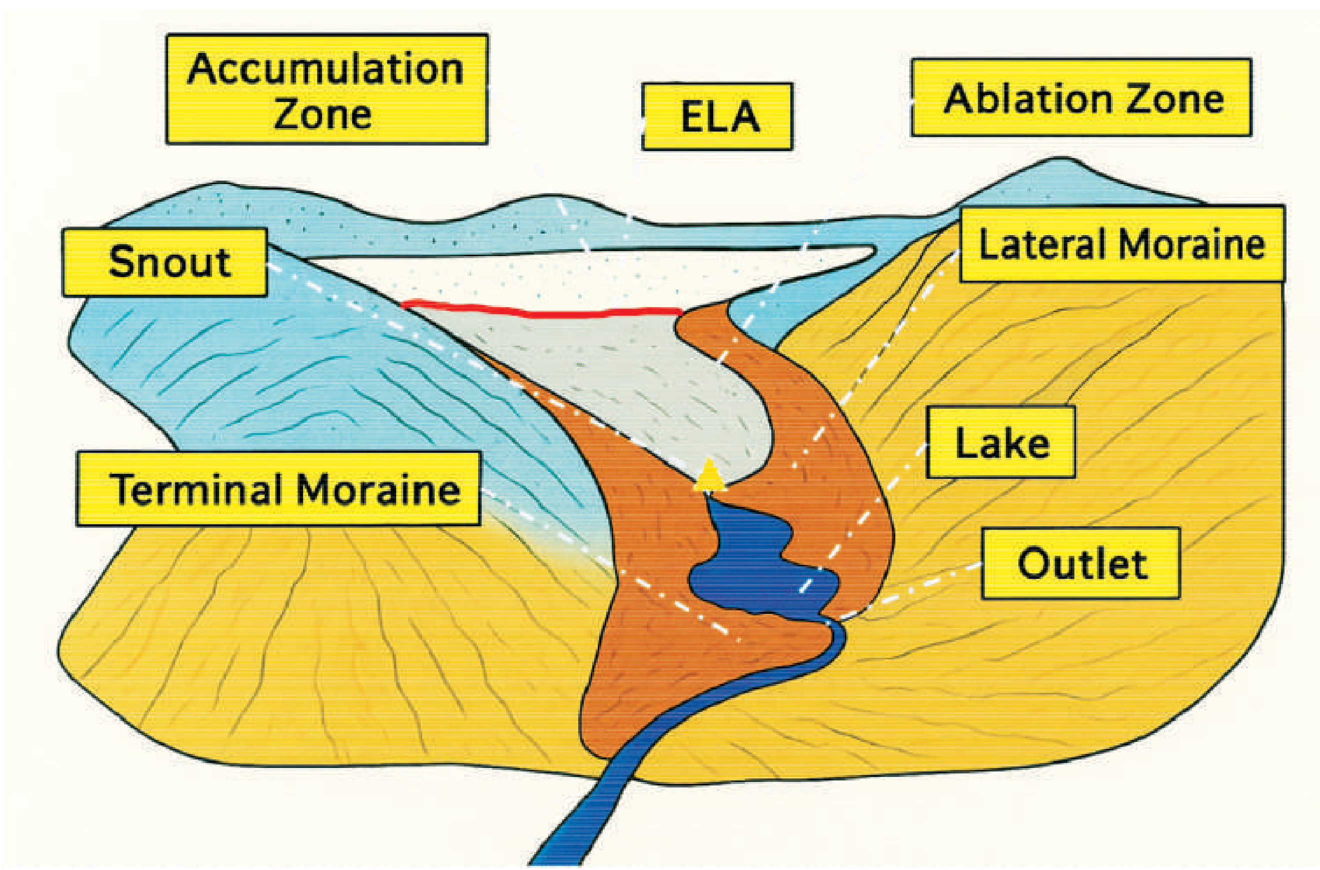

Figure 1: Schematic diagram showing the main zones and landforms of a glacier, including the accumulation zone, ablation zone, equilibrium line (ELA), snout, lateral and terminal moraines, and a proglacial lake with its outlet stream.

glacier can make the base slippery, causing the glacier to slide faster-sometimes dramatically-during warm or wet periods. The field photographs (Figure 2) illustrate key features of the Nehnar Glacier in the Jhelum Basin, including a well-defined accumulation zone, a debris-mantled ablation zone, and a prominent snout. Distinct lateral moraines, active meltwater channels, and visible ice-flow traces highlight the glacier's dynamic conditions and ongoing retreat. The inset images provide closer views of the upper accumulation area and the debris-covered terminus.

Types of Glaciers

Glaciers vary widely in their shapes, sizes, and dynamics, shaped by regional climate, surrounding topography, and the conditions that control their flow. Understanding these types helps explain why not all glaciers respond to climate change in the same way. Figure 3 provides a comprehensive visual overview of the major glacier types observed worldwide. The panel includes a combination of satellite imagery and schematic illustrations to highlight the defining characteristics, geomorphological settings, and visual distinctions among glaciers. Valley glaciers are shown confined within steep mountain valleys, while cirque glaciers appear as bowl-shaped ice bodies occupying high-altitude hollows. Piedmont glaciers are depicted as broad lobate ice masses that spill onto low-relief plains after exiting narrow valleys. Hanging glaciers are illustrated perched along steep cliff faces, often

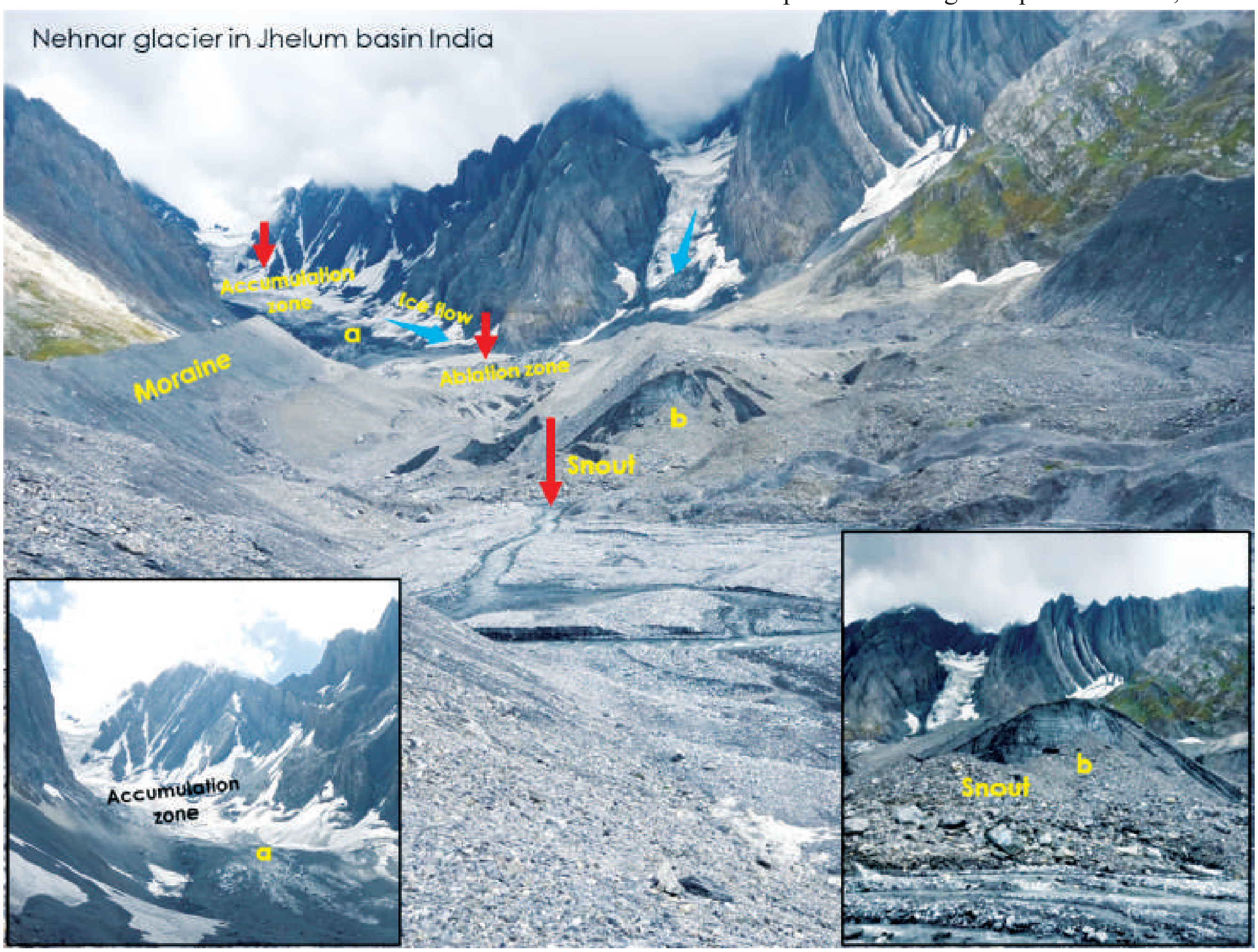

Figure 2: Field photographs of the Nehnar Glacier in the Jhelum Basin, India (Photo: Rayees Ahmed). The main image shows the accumulation zone, ablation zone, and debris-covered snout, along with prominent moraines, and meltwater channels. Panels a and b provide zoomed views of the upper accumulation zone and the snout.

disconnecting from the main glacier system. Tidewater glaciers are represented terminating directly in the ocean, where calving produces icebergs. Larger ice bodies such as ice caps and ice fields are visualised as dome-shaped and regionally extensive ice masses covering uplands. Continental ice sheets are portrayed as massive, thick ice bodies spanning large landmasses, representing the largest form of glacierised terrain on Earth. The description/definition of each glacier type is given in the Table-1.

3. Glacier Mass Balance: The Ice Budget

A glacier's health can be understood through a simple yet powerful concept known as mass balance. A glacier grows when it gains snow and shrinks when it loses ice. Mass balance is essentially the glacier's "ice budget"-the difference between what it receives and what it gives away. If more snow accumulates in winter than melts in summer, the glacier will thicken and may

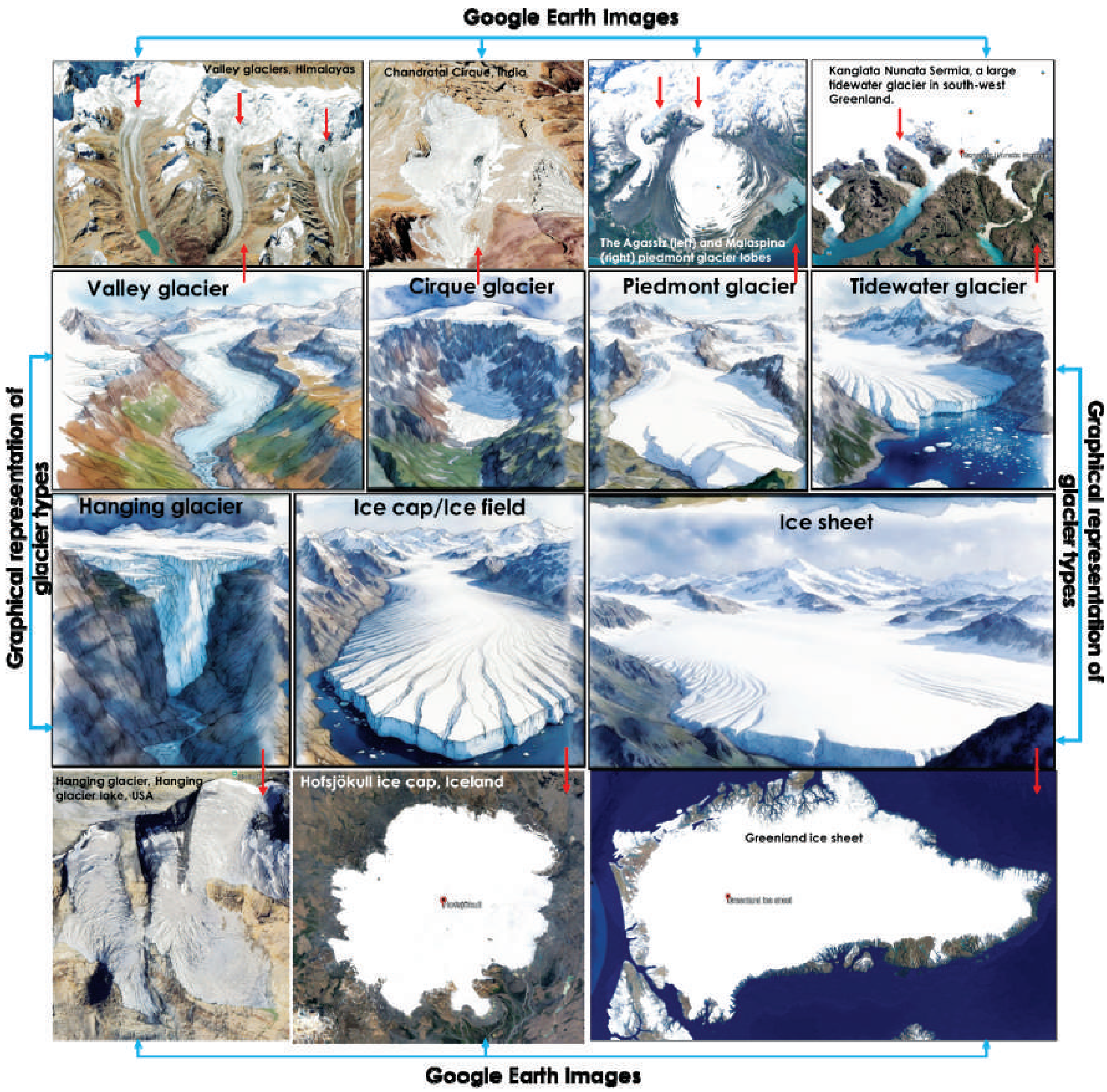

Figure 3: Overview of major glacier types based on satellite imagery and schematic illustrations, including valley, cirque, piedmont, hanging, and tidewater glaciers, along with ice caps, ice fields, and continental ice sheets.

Table-1: Description of the major types of glaciers

S.No	Type of Glacier	Description
1	**Valley Glaciers (Alpine Glaciers)**	These are glaciers that flow down mountain valleys, confined by steep rock walls. They are the most familiar type, commonly seen in the Himalaya, Alps, Rockies, and Andes. Their long tongues and narrow shapes make them sensitive to temperature changes.
2	**Cirque Glaciers**	Small glaciers that occupy bowl-shaped depressions high in the mountains. They often serve as the "birthplace" of larger valley glaciers. Many cirque glaciers are shrinking rapidly due to their small size and exposure.
3	**Piedmont Glaciers**	These form when steep valley glaciers spill onto flatter ground, spreading into broad, fan-shaped lobes. They are common in Alaska and parts of Canada.
4	**Tidewater Glaciers**	These glaciers flow all the way down to the sea and calve icebergs into the ocean. Their interaction with ocean water makes them particularly sensitive to the warming of the seas.
5	**Hanging Glaciers**	These cling to steep mountain faces and often end abruptly on cliffs. They are prone to ice avalanches and can influence hazards in steep terrain.
6	**Ice Caps**	Ice caps are dome-shaped masses of ice that cover mountain plateaus or large upland areas. They are smaller than ice sheets but still large enough to cover the underlying terrain completely. Iceland and Svalbard host prominent ice caps.
7	**Ice Sheets**	These are the largest ice bodies on Earth, covering entire continents. Only two exist today: the **Greenland Ice Sheet** and the **Antarctic Ice Sheet**. They contain the majority of the planet's freshwater ice.

advance (Lenaerts et al., 2019). But if melting outpaces snowfall-as is happening in most mountain regions today-the glacier loses mass, thins, and retreats upslope. The two components of mass balance are accumulation and ablation (Figure 4). Accumulation encompasses all the processes that add ice to the glacier, including snowfall, which is the most obvious, as well as wind-blown snow, avalanches from surrounding peaks, and the refreezing of meltwater within the snowpack. Ablation encompasses all processes that remove ice, including surface melting, evaporation, sublimation (when ice directly turns into vapour), calving of icebergs, and melting caused by rain or warm air. Each year, these processes determine whether the glacier gains or loses mass. This annual cycle is sensitive to even small shifts in temperature or snowfall, making mass balance one of the clearest indicators of climate change.

To measure mass balance, scientists employ a combination of fieldwork and remote sensing techniques. In the field, researchers place long stakes into the glacier surface and revisit them after months or a year to measure how much the ice around the stakes has melted. They also dig snow pits to measure the depth and density of winter snow. These simple yet precise measurements enable scientists to calculate the amount of ice the glacier has gained or lost. In many regions, long-term observations spanning decades show a consistent trend: shrinking mass, thinning ice, and rapidly retreating glacier fronts. Satellite methods complement these field measurements by providing a broader picture of glacier change (Yu et al., 2023).

Repeated satellite images enable researchers to calculate changes in glacier thickness, map retreating snouts, and estimate the amount of ice lost over large areas. Advanced missions, such as GRACE, can even detect changes in Earth's gravity caused by mass loss from entire glacier regions (Chen et al., 2022). Together, field and satellite observations form a highly reliable record that shows glaciers worldwide are experiencing major,

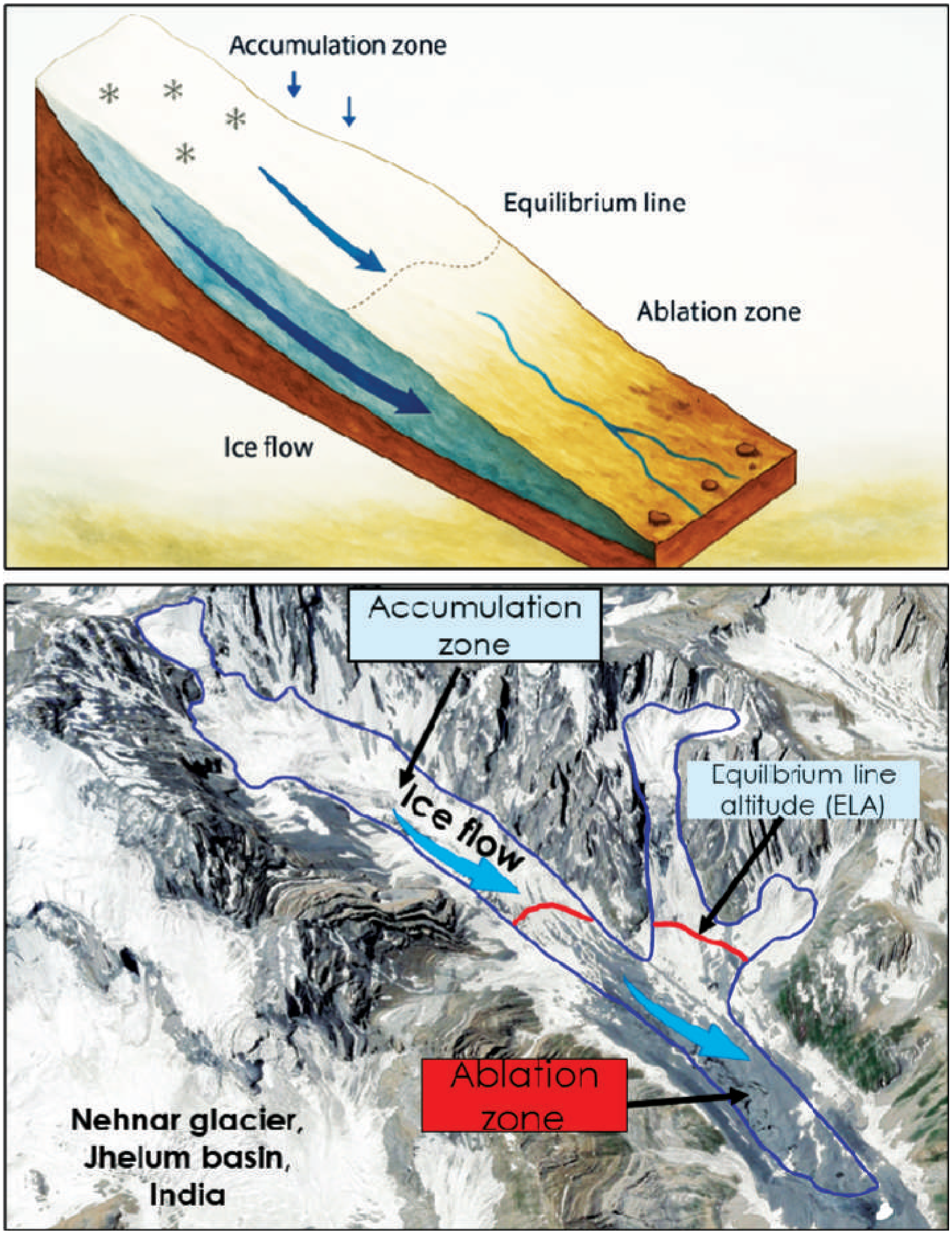

Figure 4: Schematic illustration and satellite view showing the accumulation zone, ablation zone, and ice-flow direction of Nehnar Glacier in the Jhelum basin, India. The upper diagram depicts the conceptual structure of a valley glacier, while the lower panel delineates these zones on the actual glacier using remote-sensing data

long-term negative mass balance. This isn't just a seasonal fluctuation-it is a sustained, accelerating trend driven primarily by rising temperatures.

The consequences of negative mass balance are far-reaching (Kulkarni et al., 2023). When glaciers lose mass year after year, their ability to store water declines. Meltwater initially increases for some time, a phase known as **peak water**, but once too much ice has been lost, meltwater begins to drop, reducing river flow in dry seasons (Azam et al., 2021). In high-mountain regions such as the Himalaya, where millions depend on glacier-fed rivers, this shift has serious implications for water security, agriculture, and hydropower. A negative mass balance also increases the risk of hazards such as glacial lake growth, sudden outburst floods, and the destabilisation of steep slopes once supported by ice. Understanding mass balance helps society anticipate how glaciers will respond to future climate conditions. It also highlights a critical reality: glaciers are changing right now, and these changes are directly linked to rising temperatures. Mass balance, though a simple concept, provides one of the clearest windows into how climate change is reshaping the world's frozen landscapes. Glaciers are highly sensitive indicators of climate change, responding to both natural variability and human influences across local to global scales. Warming driven by greenhouse gas emissions (ISM) increases air temperatures and enhances snow/ice melt, while black carbon deposition from industrial and biomass burning darkens glacier surfaces, accelerating absorption of solar radiation. Simultaneously, changing patterns of the Indian Summer Monsoon (IWM) alter precipitation amounts and the rain-snow ratio at high elevations. Together, these forcings reduce glacier volume and area, thin permafrost, and shift glacier dynamics, ultimately decreasing meltwater contribution to downstream rivers, diminishing groundwater recharge, and amplifying water stress in densely populated basins (Figure 5).

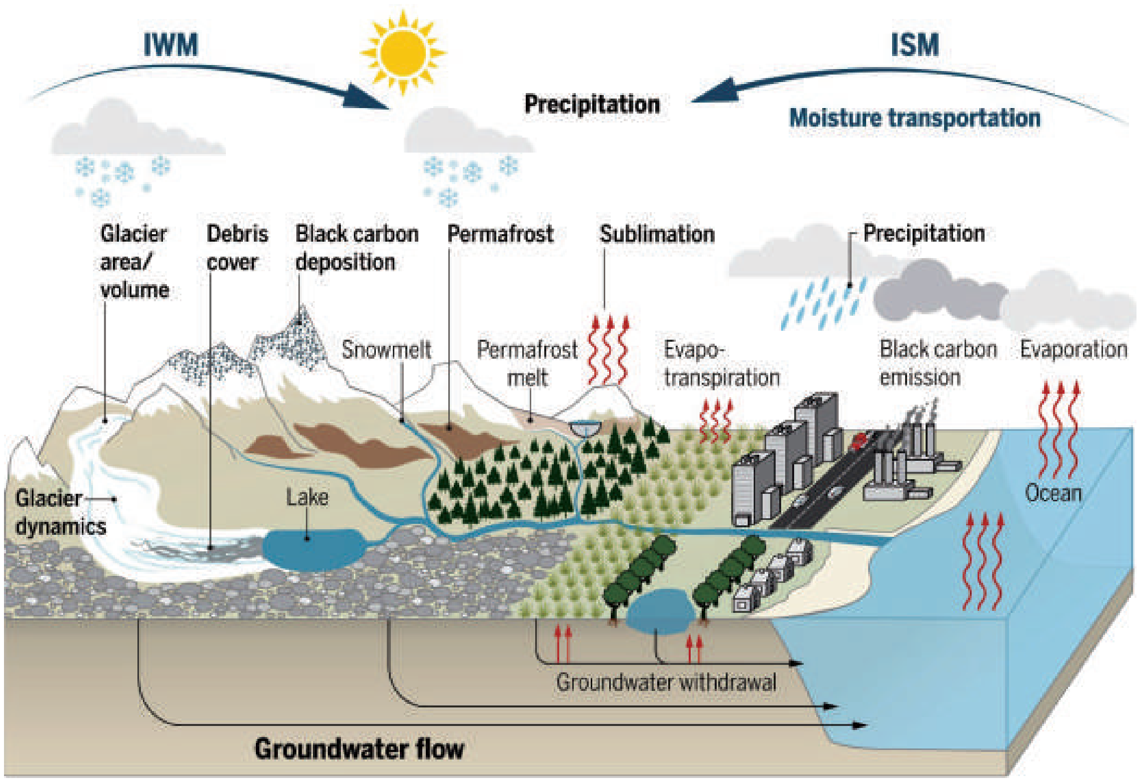

Figure 5: Schematic illustration of the major natural and anthropogenic drivers affecting Himalayan glaciers and downstream water resources. Climate forcing from the Indian Summer Monsoon (IWM) and global anthropogenic emissions (including black carbon and greenhouse gases) interact with local processes, such as debris cover, permafrost thawing, and surface darkening, to control glacier volume, melt rates, and dynamics. Changes in glacier storage ultimately influence meltwater runoff, groundwater recharge, lake formation, and water availability across the Himalayan-Indo-Gangetic system (*adapted from Azam et al., 2021*).

4. How Scientists Study Glaciers

Studying glaciers is both challenging and fascinating. These massive bodies of ice often lie in remote, high-altitude regions where weather is harsh and access is difficult. Yet, because glaciers are such important indicators of climate and vital sources of water, scientists have developed a wide range of methods to understand how they behave, how fast they are melting, and how their changes might affect downstream communities. Modern glacier research combines traditional fieldwork with advanced satellite technologies and computer models, providing scientists with a detailed and evolving picture of the world's ice.

4.1 Field Measurements: Science on the Ice

For over a century, fieldwork has been the cornerstone of glacier science. Researchers travel to the glacier surface-often on foot, using ropes, crampons, and sometimes helicopters-to make direct measurements. One of the most common methods is the use of **ablation stakes**, which are long poles drilled into the ice (see Figures 6a and 6b). By revisiting these stakes each year, scientists can measure how much the ice surface has lowered due to melting. In the accumulation zone, snow pits are dug to measure the depth, density, and structure of winter snow. These measurements indicate the amount of snow that has accumulated on the glacier throughout the season. Fieldwork also includes GPS surveys to track glacier movement, the installation of automatic weather stations to record temperature and radiation (Figure 6c and 6d), and the collection of water samples from melt streams to understand how water flows through and beneath the glacier. Though physically demanding, these direct observations offer precise, ground-level insights. They form the backbone of long-term glacier monitoring programs in the Alps, Himalaya, North America, Scandinavia, and other mountain regions.

4.2 Remote Sensing: A Bird's-Eye View of Ice

Because fieldwork is time-consuming and often limited to specific locations, remote sensing from satellites has revolutionised glacier monitoring by providing a bird's-eye view over thousands of glaciers in vast and inaccessible regions. High-resolution optical imagery from satellites such as Landsat, Sentinel-2, and ASTER enables scientists to delineate glacier boundaries, track areal changes, and observe seasonal snow cover, revealing retreating fronts, expanding glacial lakes, and newly exposed terrain through multi-year image comparisons. Paired stereo images from the same satellites are processed into digital elevation models (DEMs), and by subtracting older DEMs from newer ones-a technique known as DEM differencing-researchers quantify surface lowering or thickening over time. Satellites like NASA's ICESat and ESA's CryoSat employ laser and radar altimetry, sending pulses to the surface and timing their return to detect subtle elevation changes even under persistent cloud cover. Meanwhile, interferometric synthetic aperture radar (InSAR) utilises radar phase differences to measure minute surface displacements, enabling the mapping of glacier flow velocities, the identification of surge events, and the monitoring of deformation across entire ice fields.

4.3 Gravity-Based Measurements: Seeing Ice by Its Weight

One of the most remarkable tools for studying glaciers is the GRACE (Gravity Recovery and Climate Experiment) satellite mission. Instead of taking pictures, GRACE measures tiny variations in Earth's gravity field. When glaciers lose mass, the gravity in that region weakens slightly. By detecting these changes, GRACE and its successor, GRACE-FO, can estimate mass loss from entire mountain ranges-such as the Himalaya, Alaska, or Patagonia-even when individual glacier measurements are impossible. These datasets have revealed that many regions are losing ice at accelerating rates.

4.4 Computer Models: Simulating the Future of Glaciers

Models help scientists predict how glaciers might change under different climate scenarios. Using data from fieldwork and satellites, models simulate ice flow,

Figure 6: a) Researchers installing ablation stakes on the glacier surface in the western Jhelum basin, India, using a Huckes drill (Photo: Mifta ul Shafiq). b) Huckes ice drill and aluminium stakes prepared for installation. c) Snout of Samudra Tapvan Glacier, Lahaul and Spiti district, Himachal Pradesh (Photo: Anil Kulkarni). d) Automatic weather station installed in the accumulation zone at 5218 m a.s.l. on Chhota Shigri Glacier (Photo: Himanshu Kaushik).

melting processes, snow accumulation, and the formation of glacial lakes. These tools are essential for understanding future water availability, forecasting hazards, and exploring how glaciers respond to warming temperatures. As climate models improve and more observational data becomes available, glacier models become increasingly accurate.

4.5 Integrated Monitoring: A Complete Picture

No single method can fully capture the complexity of glacier behaviour. Instead, scientists combine multiple approaches: field observations reveal detailed local processes, satellite data cover large remote regions, gravity measurements detect broad-scale mass loss, and models integrate all of these to predict future changes. Together, these tools provide a comprehensive understanding of how glaciers are evolving and how their changes will shape water resources, landscapes, and communities in the years to come.

5. How Glaciers Store and Release Water

Glaciers are more than frozen rivers-they act as natural reservoirs, storing and releasing water across multiple timescales. In mountain regions such as the

Himalaya, Andes, and Central Asia, glaciers accumulate snow and ice during cold months and release meltwater during warmer seasons, sustaining river flows even when rainfall is scarce. The largest form of glacier water storage is solid ice, formed as snow compacts over decades, while firn-the transitional snow-ice material-also retains water in its pores (Humbert, 2024). This long-term storage regulates regional water supplies and, when lost through melting, contributes to sea-level rise, making it a key indicator of climate change. Glaciers also provide seasonal storage through snowpacks, which melt gradually in spring and summer, feeding rivers when rainfall is low (Milner et al., 2009). On shorter timescales, meltwater collects within crevasses, englacial channels, and subglacial cavities, temporarily stored before escaping, and can influence glacier movement by lubricating the bed and increasing sliding (Kenner et al., 2022). Not all stored water is released gradually; sometimes sudden events such as glacial lake outburst floods, subglacial floods, or ice-dammed lake failures occur, causing flash floods and threatening downstream communities. As glaciers retreat, the frequency and magnitude of such events are increasing, particularly in the Himalaya (Veh et al., 2020). Glacier storage is crucial for stabilising river flows, supporting agriculture, and maintaining hydropower generation (Farinotti et al., 2019). However, as glaciers shrink, their capacity to store water diminishes, and many basins may reach "peak water," where initial increases in meltwater are followed by long-term declines (Azam et al., 2021). Understanding how glaciers store and release water across daily, seasonal, and long-term timescales is therefore essential for predicting future water availability, managing risks, and sustaining ecosystems and communities downstream.

6. Global Glacier Retreat: What Is Happening Now

Around the world, glaciers are retreating at a pace never observed in recorded history. From the towering Himalaya to the European Alps, from the Andes to Alaska, and from the Rockies to remote Arctic islands, the story is the same: glaciers are shrinking, thinning, and retreating upslope (Pole, 2022). This global pattern has been confirmed through decades of field measurements, satellite observations, and long-term monitoring programs. Although individual glaciers may behave differently from year to year depending on local weather, the overall trend is unmistakable-glacier loss is accelerating, and it is occurring nearly everywhere. Glaciers outside Greenland and Antarctica are losing mass rapidly, with 267 ± 16 Gt yr^{-1} lost during 2000-2019 and accelerating thinning rates. Regional patterns reflect climate variability, providing critical benchmarks for predicting glacier change and guiding water-resource and sea-level management (Hugonnet et al., 2021). Regionally, seven glacierised areas account for 83% of global glacier mass loss, with Alaska (25%) and the Greenland Periphery (13%) leading. Specific-mass change rates varied strongly with latitude, from moderate losses in the northernmost Arctic (-0.28 ± 0.04 m w.e. yr^{-1}) to the largest losses in southern Arctic regions and Iceland (up to -0.88 ± 0.13 m w.e. yr^{-1}), while High Mountain Asia and the Antarctic exhibited the least-negative rates (-0.22 ± 0.05 and -0.17 ± 0.04 m w.e. yr^{-1}, respectively) (Figure 7). These estimates broadly agree with gravimetric and in situ measurements, though discrepancies exist in regions with sparse observations, such as Iceland, the Russian Arctic, High Mountain Asia, and the Southern Andes.

Glacier retreat began around the end of the Little Ice Age (~mid-1800s) as global temperatures rose, but the most dramatic losses have occurred in recent decades. Satellite records since the 1970s have shown steady reductions in glacier area and length, while GRACE and other missions have revealed accelerated ice mass loss since the early 2000s in regions such as Alaska, western Canada, Patagonia, the European Alps, and High Mountain Asia (Ciraci et al., 2020). Some glaciers now lose several meters of thickness annually (Farinotti et al., 2019). A clear indicator of retreat is the formation of proglacial lakes, which are expanding rapidly in the Himalaya, Andes, and Central Asia.

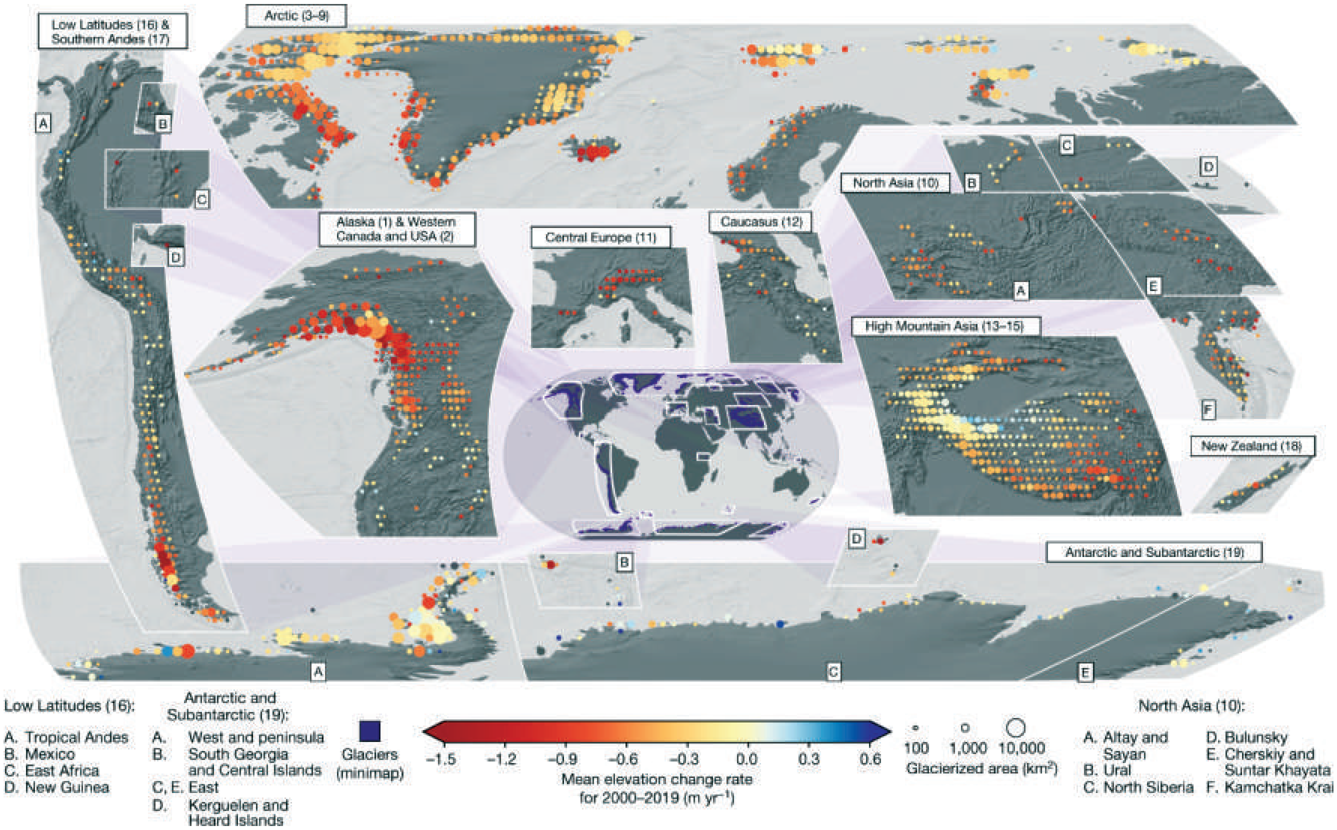

Figure 6: Global glacier mean elevation change rates (2000–2019) shown for 1°-2° tiles, scaled by glacierised area (circle size) and coloured by mean change (m/ yr^{-1}). Grey indicates tiles with <50% glacier coverage or high uncertainty. Insets highlight major glacierised regions: Low Latitudes & Southern Andes (16-17), Arctic (3-9), Alaska & Western Canada/ USA (1-2), Central Europe (11), Caucasus (12), North Asia (10), High Mountain Asia (13-15), New Zealand (18), and Antarctic/Subantarctic (19). Figure adapted from Higgonet et al., 2021.

Glacier termini now end far upstream, exposing bare rock and sediments, and rapidly transforming the landscape. This retreat is primarily driven by climate change. Rising temperatures extend melt seasons, while altered precipitation reduces snow accumulation. Deposited dust and black carbon darken ice surfaces, further accelerating melt, especially in the Himalaya and Tibetan Plateau. Exceptions exist, such as parts of the Karakoram Range, where some glaciers remain stable or advance slightly (the Karakoram Anomaly), highlighting the role of local climate, debris cover, and valley geometry. Globally, however, most glaciers are losing mass rapidly. Glacier loss contributes significantly to sea-level rise, reshapes mountain landscapes, destabilises slopes, alters ecosystems, and affects communities reliant on glaciers for water, livelihoods, or cultural identity (Hugonnet et al., 2021). Their retreat is a visible indicator of a warming planet and underscores the need for ongoing monitoring and climate adaptation planning.

7. Why Glaciers Are Melting Faster

Glaciers worldwide are melting faster than at any time in modern history due to a combination of rising temperatures, shifting precipitation patterns, and surface processes that amplify ice loss (Rounce et al., 2023). Global warming remains the dominant driver, and high-mountain regions are warming at rates higher than the global average. Because many glaciers exist close to the freezing point, even small increases in temperature lengthen the melt season, accelerate snowmelt, reduce the number of freezing nights, and enhance overall mass loss. Changing precipitation regimes further intensify this trend: winters that once brought substantial snowfall increasingly deliver rain, reducing accumulation and limiting glaciers' ability to rebuild annually. In the Himalaya, evolving monsoon and westerly patterns have altered both the timing and amount of winter snowfall, leaving many glaciers more vulnerable to enhanced melt.

These climate-driven processes are clearly reflected in the behaviour of the Geepang Gath Glacier in the western Himalaya. Satellite imagery shows that the glacier's snout retreated by 637 m between 2010 and 2025, equivalent to an average rate of ~42 m yr^{-1}, highlighting rapid frontal recession. At the same time, the proglacial lake expanded from 0.67 km^2 in 2010 to 1.11 km^2 in 2025, demonstrating how sustained meltwater input and thermal undercutting at the terminus promote both glacier retreat and lake growth (Figure 7). The expanding lake further absorbs heat, destabilises the glacier front, and accelerates melt-creating a feedback that contributes to faster retreat. Additional environmental factors also accelerate glacier melt. Deposition of dust, soot, and black carbon reduces surface albedo and increases solar energy absorption, particularly across the Himalaya and Tibetan Plateau. Reduced seasonal snow cover exposes bare ice earlier in the year, while more frequent rain-on-snow events deliver warm water that enhances surface and internal melting. In maritime and polar regions, tidewater glaciers are further impacted by warming oceans that erode their fronts from below, triggering rapid calving and large-scale retreat, as observed in Alaska, Greenland, and Patagonia. Together, these interacting drivers explain why glaciers are melting faster today than in the past, with consequences that extend far beyond the ice-shaping water resources, lake development, natural hazards, and the livelihoods of communities dependent on glacier-fed systems.

8. Impacts on Water, People, and Hazards

The retreat of glaciers is reshaping mountain regions in ways that extend far beyond changes in meltwater supply. As glaciers shrink, watersheds undergo a fundamental reorganisation: rivers that were once buffered by slow, predictable melt now respond more directly to rainfall and short-term weather extremes. This shift increases hydrological volatility, creating sharper seasonal contrasts and making downstream communities more vulnerable to both sudden shortages and intense monsoon-driven floods. In many basins, these changes occur long before a glacier disappears-early warning signs include the shortening of the melt season, altered timing of peak flows, and increased dependence on rainfall rather than meltwater during critical agricultural periods (Figure 8).

The landscape effects of glacier loss are equally transformative. Newly exposed valley floors and steep, freshly deglacierized slopes are unstable and highly sensitive to disturbance. These emerging "post-glacial terrains" behave differently from traditional mountain landscapes: they erode more rapidly, host immature soils, and respond strongly to intense rainfall, often producing sediment-rich floods that overwhelm rivers and reservoirs downstream. As proglacial lakes expand, their growing depth and thermal structure generate new microclimates in upper valleys, influencing local wind patterns, humidity, and frost occurrence-subtle but important feedbacks that shape land use, vegetation recovery, and human activity in high-altitude settlements. Hazard profiles are also shifting from single events to complex, cascading chains. A modest landslide can now trigger displacement waves in glacial lakes, which in turn may destabilise moraine dams or send surges of sediment downstream. These connected hazards evolve rapidly and often unfold without clear precursors, making them difficult to monitor with traditional early-warning systems. As mountain slopes lose the structural support once provided by ice and permafrost, entire valley sides are beginning to deform, creating slow-moving but persistent threats to villages, trekking routes, hydropower tunnels, and transportation corridors. The impacts extend to governance and resource planning, areas often overlooked in glacier studies. Water-sharing agreements, hydropower strategies, and irrigation schedules-many designed

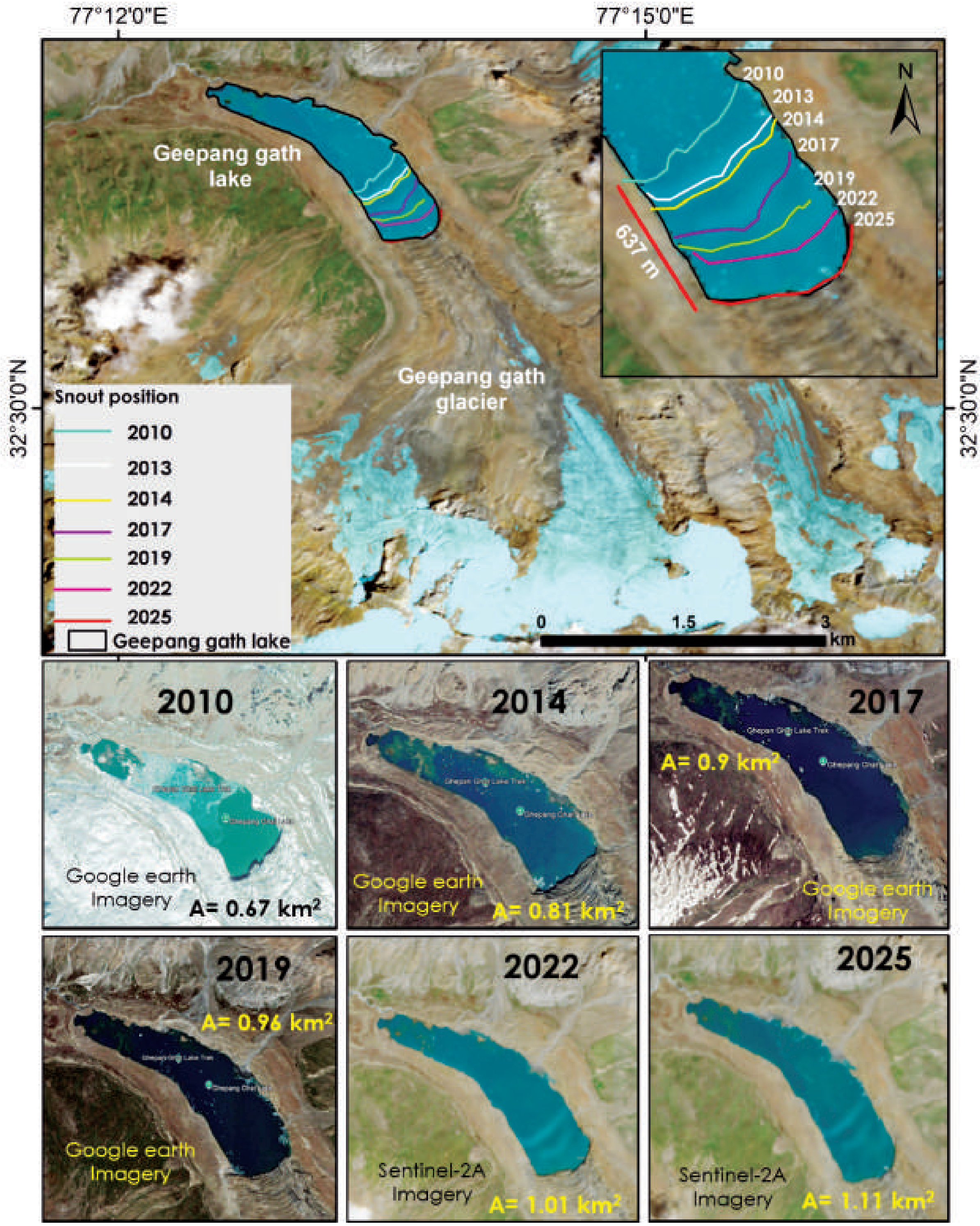

Figure 7: Rapid glacier retreat and proglacial lake expansion: an example from the Geepang Gath Glacier-Lake system, Himachal Pradesh, India. (Top) Mapped extents of the Geepang Gath Lake and snout positions of the Geepang Gath Glacier from 2010 to 2025, illustrating pronounced glacier retreat and accelerating lake growth. The glacier snout receded by 637 m during this period, coinciding with continuous lake expansion. Annual lake outlines show a steady increase in area from 0.67 km² (2010) to 1.11 km² (2025). (Bottom) High-resolution Google Earth and Sentinel-2A imagery for selected years (2010, 2014, 2017, 2019, 2022 and 2025) depict the progressive enlargement of the proglacial lake and the retreating glacier front, demonstrating the strong geomorphic response of the glacier–lake system to recent warming in the region.

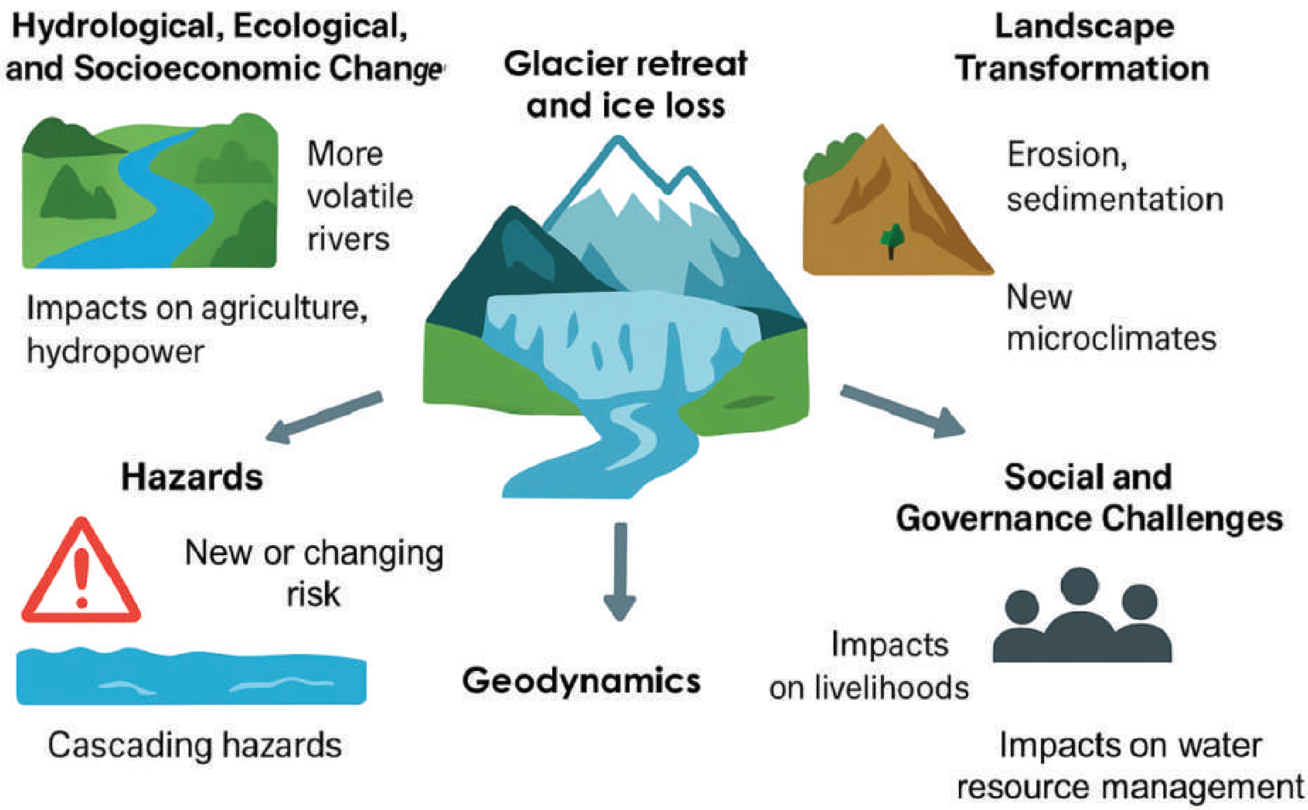

Figure 8: Conceptual diagram illustrating the multifaceted consequences of glacier retreat and ice loss, including hydrological, ecological, socioeconomic, and governance-related impacts, as well as landscape transformation and emerging natural hazards.

decades ago-were based on the assumption of stable seasonal melt. As meltwater becomes more erratic, these agreements are strained, and in some regions, competition for water is intensifying. Mountain communities, which have long relied on predictable seasonal rhythms, are being forced to reconfigure cropping calendars, grazing routes, and household water storage practices to cope with shifting hydrological regimes.

Culturally, the loss of ice is reshaping the ways communities relate to their landscapes. Glaciers have traditionally served as markers of identity, spiritual sites, weather guides, and sources of local knowledge. Their disappearance alters the memory and meaning of place, especially among Indigenous groups whose oral histories are tied to the presence of long-standing ice masses. Tourism economies also face an uncertain future: while retreating glaciers initially attract attention, their eventual degradation often diminishes the scenic value that sustains local businesses. Although these transformations are most visible in high mountains, their influence is ultimately global. Glacier decline remains a major contributor to sea-level rise, while the sediment and water released from deglaciating basins alter downstream river morphology, delta stability, and coastal ecosystems. These cascading, interconnected impacts highlight that glacier retreat is not merely an environmental trend-it is a profound reconfiguration of social-ecological systems, with consequences that span mountains, cities, and coastal regions alike.

9. The Himalaya-A Regional Perspective

The Himalaya holds one of the largest reserves of ice outside the Arctic and Antarctic. Stretching across eight countries-India, Nepal, Bhutan, China, Pakistan, Afghanistan, Myanmar, and Bangladesh-the Himalayan region forms the headwaters of some of Asia's greatest rivers, including the Indus, Ganga, Brahmaputra, Mekong, and Yangtze. These rivers support nearly two billion people, making the Himalaya not only a geophysical giant but a lifeline for one of the world's most densely populated regions (Harrison et al., 2024). As glaciers in this region undergo rapid environmental change, the impacts are felt far beyond the high mountains. Himalayan glaciers are highly diverse, shaped by the interaction of monsoon systems, the westerlies, extreme topography, and high elevation (Yadav et al., 2021). Many of these glaciers are summer-accumulation type, meaning they receive most of their snow during the monsoon season, unlike many other mountain regions where snowfall peaks in winter. This unique climate sensitivity makes Himalayan glaciers more vulnerable to warming, as higher temperatures during the same season also intensify melting. A defining feature of the region is the prevalence of debris-covered glaciers, particularly in the central and eastern Himalaya (Ojha et al., 2017). Thick layers of rocks and sediment insulate the ice beneath, slowing melt in some places but accelerating it in others by forming melt ponds, exposed ice cliffs, and complex surface dynamics (Upadhyay, 2025). These features create highly uneven melt patterns, making Himalayan glaciers highly sensitive and sometimes unpredictable compared to clean-ice glaciers. Over the past few decades, glaciers across much of the Himalaya have shown widespread retreat, thinning, and mass loss (Chand et al., 2021). Many glaciers have retreated by hundreds of meters, with some losing tens of meters of ice thickness. Remote sensing studies indicate that the rate of loss has accelerated since the 2000s, mirroring global trends but with regional variations. In the Eastern Himalayas, where the monsoon influence is strong, glaciers are among the fastest-retreating (Ahmed et al., 2023). The Central Himalaya, including Nepal and Uttarakhand, shows dramatic thinning and rapid growth of glacial lakes (Khadka et al., 2023). The Western Himalaya experiences more complex trends, partly due to winter westerlies, but significant retreat is still evident across many basins. The Karakoram Range in the northwest remains an exception, with some glaciers-known as the Karakoram Anomaly-remaining stable or slightly advancing, driven by unique local climatic conditions.

One of the most visible consequences of Himalayan glacier retreat is the rapid formation of proglacial lakes (Sattar et al., 2025; Ahmed et al., 2025). These lakes have multiplied and expanded dramatically in the last few decades, filling depressions left by retreating glacier fronts. Some lakes in Nepal, Bhutan, and the eastern Himalaya have grown to several kilometers in length (Komori, 2008; Shukla et al., 2018). This expansion increases the risk of GLOFs, now recognised as one of the major climate-related hazards in the region. Well-known examples-from Dig Tsho (1985) in Nepal to the recent South Lhonak GLOF in Sikkim in 2023-underscore the region's sensitivity. As the climate warms, the number of potentially dangerous lakes continues to rise, especially in the central and eastern Himalaya.

The Himalaya's glaciers play a critical role in feeding the major river systems of South and Southeast Asia. Meltwater regulates flows during spring and summer, providing water for irrigation, hydropower, and household use (Azam et al., 2021). In basins such as the Indus, meltwater contributes significantly to total river discharge, supporting agriculture in some of the driest regions of South Asia. However, as Himalayan glaciers shrink, the region is slowly transitioning toward peak water, after which meltwater contributions will begin to decline. This shift threatens water availability for millions of people dependent on glacier-fed rivers. The impacts will not be uniform: some basins may see reduced summer flows, while others may experience greater seasonal variability, complicating water management and planning.

The Himalayan landscape is steep, young, and geologically active. As ice thins and retreats, slopes lose the mechanical support once provided by glaciers. Combined with the thawing of high-altitude permafrost, this leads to increased rockfalls, landslides, and debris flows. Many recent disasters-such as collapses of hanging glaciers, ice-rock avalanches, and failures of steep headwalls-are linked to destabilisation driven by warming temperatures. For Himalayan communities, glaciers hold deep cultural and spiritual value. They are woven into local traditions, belief systems, and everyday livelihoods. As glaciers shrink or disappear, communities not only lose a crucial water source but also a part of their cultural identity. Tourism-an economic lifeline in Nepal, Bhutan, and parts of India-is also affected as iconic glaciers retreat or become hazardous to access. The Himalaya is warming at a rate higher than the global average, making it one of the most climate-sensitive regions on Earth. Its glaciers, lakes, and landscapes respond rapidly to these changes. The combination of high population density downstream, fragile mountain terrain, and accelerating glacier loss means that the Himalayan region sits at the frontline of climate risk. The lessons learned here-about water, hazards, adaptation, and resilience-hold importance not just for local communities but for the entire world.

10. The Way Forward-Research, Monitoring, and Adaptation

As glaciers continue to shrink across nearly all mountain regions, the need for coordinated scientific research, sustained monitoring, and community-centred adaptation has become increasingly urgent. Glaciers play a critical role in regulating freshwater supply, shaping mountain hazards, sustaining river ecosystems, and contributing to global sea-level rise. Their rapid retreat is fundamentally altering these systems, making it essential to adopt a proactive, science-based approach that integrates long-term observations, improved predictive models, hazard management, and strategies that strengthen the resilience of downstream communities (Figure 9). The path forward depends on enhancing research capacity, expanding early-warning systems, and ensuring that vulnerable populations have the resources, institutional support, and scientific information needed to navigate accelerating environmental change.

10.1 Strengthening Glacier Monitoring

Long-term, consistent monitoring is the backbone of glacier science, yet many glacierised basins-particularly in the Himalaya, Andes, and Central Asia-remain severely under-observed. Addressing this requires a substantial expansion of both in situ and remote-sensing observations. Field-based measurements such as glaciological mass balance, snow-pit surveys, ice-velocity measurements, and automatic weather stations provide precise, ground-level insights into how glaciers respond to climate forcing. These observations help validate satellite products and improve the performance of numerical models. At the same time, modern satellite missions such as Landsat, Sentinel-1/2, ICESat-2, CryoSat-2, and GRACE have revolutionised cryospheric monitoring. Optical and radar imagery allow researchers to track changes in glacier area, thickness, and flow, while GRACE gravimetry detects mass loss at the basin and regional scales. Combining space-based datasets with field observations produces robust multi-decadal records that underpin glacier inventories, hazard assessments, and policy-relevant climate reporting.

10.2 Advances in Modeling and Prediction

As glacier change accelerates, numerical modeling has emerged as an indispensable tool for projecting future glacier behaviour and its hydrological and geomorphic consequences. Modern glacier models simulate key processes including surface mass balance, ice flow mechanics, basal sliding, the influence of debris cover, meltwater routing, and the emergence of glacial lakes. When driven by high-resolution climate projections, these models provide insights into when basins may reach peak water and how water availability will shift thereafter. They also support hazard forecasting by simulating the downstream impacts of glacial lake outburst floods, avalanche-induced lake surges, and moraine-dam failures. Advances in hydrodynamic modeling now allow researchers to predict inundation patterns, sediment loads, and flood arrival times with increasing accuracy. Together, these tools help identify regions that are likely to face declining water availability or heightened disaster risk in the coming decades.

10.3 Managing Glacial Lake Hazards

The rapid expansion of glacial lakes is one of the most visible consequences of glacier retreat, and it requires systematic and coordinated hazard assessments. Monitoring lake evolution, identifying unstable moraine dams, assessing potential triggers such as ice avalanches, earthquakes, or extreme rainfall, and understanding lake thermal dynamics are essential steps in risk reduction. In many Himalayan countries, early-warning systems have begun to play a transformative role by providing real-time alerts to downstream communities. Engineering interventions have also proven effective in certain contexts, including controlled lake lowering, siphoning, and the reinforcement of moraine dams. These measures, successfully implemented in Nepal and Bhutan, demonstrate that hazard mitigation is possible but must be accompanied by careful engineering design, regular maintenance, and meaningful engagement with local communities who ultimately bear the risks.

Figure 9: Framework illustrating the six interconnected components essential for glacier monitoring, modelling, hazard assessment, policy integration, regional collaboration, and community adaptation.

10.4 Supporting Communities and Local Adaptation

Communities living in glacier-fed basins are among the first to experience the impacts of rapid cryospheric change, making local adaptation a central component of any long-term strategy. Strengthening adaptive capacity begins with improving local awareness of glacier hazards, fostering preparedness, and co-developing solutions with the people directly affected. Disaster-response planning, resilient infrastructure, water-resource diversification, and climate-smart agricultural practices are increasingly important as hydrological regimes become more unpredictable. Many communities are now forced to adjust cropping calendars, modify grazing patterns, and adopt water-conservation practices to cope with altered meltwater supply. Supporting alternative livelihoods is equally critical in regions where tourism, agriculture, or pastoralism are disrupted by glacier retreat or increasing hazard frequency. Integrating traditional and Indigenous knowledge with scientific approaches enhances the relevance and acceptance of adaptation strategies, as mountain communities often possess a deep observational understanding of glacier behaviour, river flow patterns, and local weather variability.

10.5 Regional Collaboration and Data Sharing

Because glaciers and their associated river systems transcend political boundaries, their management necessitates robust regional cooperation and a shared scientific framework. The transboundary exchange of climate data, glacier observations, water flow records, and hazard information enhances preparedness and supports coordinated response strategies during extreme events. Regional organisations such as ICIMOD, UNESCO, UNDRR, WMO, and national research institutions play an essential role in facilitating collaboration, training scientists, harmonising methodologies, and supporting the development of regional glacier inventories and hazard maps. Strengthening these partnerships helps ensure that scientific advances are equitably shared and that research findings translate into meaningful, region-wise solutions rather than fragmented, country-specific actions.

10.6 Integrating Science into Policy

Effective glacier-related decision-making relies on policies based on up-to-date scientific knowledge. Governments should incorporate glacier research into their national frameworks for climate adaptation, water management, disaster risk reduction, and mountain ecosystem protection. This includes updating municipal planning in hazard-prone valleys, designing hydropower infrastructure based on future meltwater scenarios, and protecting headwater ecosystems that act as natural buffers for erosion and sediment transport. Long-term water security strategies must consider shifts in meltwater timing and volume, particularly as many basins approach or surpass their peak water levels. Embedding glacier science into policy frameworks ensures that climate risks are managed proactively rather than reactively.

10.7 A Global Responsibility

While regional and local actions are crucial, the ultimate drivers of glacier retreat stem from global climate change. Reducing greenhouse gas emissions is the most effective way to slow glacier loss and limit long-term impacts on water resources, ecosystems, and mountain hazards. Mitigation must be complemented by efforts to reduce black carbon emissions, protect mountain ecosystems, and promote sustainable development in high-altitude regions. Glaciers are more than frozen landscapes-they are irreplaceable freshwater reserves, cultural symbols, and indicators of planetary health. The responsibility to protect them extends beyond national borders and is shared by the global community. With coordinated action, informed scientific planning, and strengthened community resilience, society can navigate the challenges posed by glacier retreat and contribute to a more secure and sustainable future.

11. Conclusion

Glaciers, once regarded as timeless symbols of stability, are now among the planet's fastest-changing features. Their retreat is not a distant or abstract problem-it is a clear and measurable signal of a warming climate, visible in every major mountain region. From the Himalaya to the Andes and the Alps, glaciers are shrinking, thinning, and reshaping entire landscapes. These changes affect far more than high-mountain environments: they influence water resources for millions of people, alter river systems, increase the risk of floods and landslides, and disrupt ecosystems that depend on cold, meltwater-fed streams. At the same time, glaciers are powerful storytellers of environmental change. Their mass balance records, shifting snowlines, and expanding glacial lakes provide some of the most direct evidence of how Earth's climate is evolving. Understanding these changes requires a combination of detailed field observations, advanced satellite monitoring, and improved models that can anticipate future scenarios. The scientific community has made remarkable progress in this direction, but large knowledge gaps remain-particularly in remote and complex regions like the Himalaya, where data scarcity still limits our understanding.

The impacts of glacier retreat are already unfolding, and they will become more pronounced in the coming decades. Many river basins are approaching or have already reached peak water, after which meltwater contributions will decline. This shift poses significant challenges for agriculture, hydropower, drinking water supply, and regional planning. Meanwhile, the growth of glacial lakes, destabilisation of steep slopes, and thawing of permafrost increase the frequency and intensity of natural hazards. These risks underscore the importance of investing in early-warning systems, improved hazard mapping, robust infrastructure, and community-led adaptation strategies. Yet, the story of glaciers is not solely about loss-it is also about opportunity and responsibility. The rapid changes in glacier environments present an opportunity to enhance scientific collaboration, enhance mountain monitoring systems, and foster resilience in vulnerable regions. By integrating local knowledge with scientific research, empowering communities with hazard awareness, and incorporating glacier data into climate and water policies, societies can better prepare for a future shaped by diminishing ice.

Ultimately, slowing the rate of glacier loss requires global action. Reducing greenhouse gas emissions, protecting mountain ecosystems, and committing to long-term climate goals remain essential. While glaciers may continue to retreat for some time due to the warming already locked into the climate system, decisive action today can limit further loss and reduce the severity of future impacts. Glaciers are more than frozen landscapes-they are vital freshwater reserves, climate indicators, cultural symbols, and ecosystems in their own right. Their fate is intertwined with our own. Understanding, monitoring, and protecting them is not just a scientific challenge but a shared global responsibility. The choices we make now will determine the future of the world's glaciers and the communities and environments that depend on them.

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SECONDARY RARE EARTH ELEMENT (REE) DEPOSITS: INSIGHTS ON REE TRANSIT AND DEPOSITION

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ABSTRACT

Over the years, rare earth elements (REE) have been used as powerful petrogenetic tool to understand the Earth's internal and external processes. However, with the ongoing energy transition towards green technologies, the demand for REE resources has reached a peak globally. Though these resources are widespread across all the continents, their heterogenous distribution has created geopolitical issues between different countries, and India is keen to become self-sustained to meet the growing REE demand and to achieve zero carbon future. Most organizations in our country are at the forefront of identifying new deposits using various exploration methods and adopting innovative mining and processing technologies. In this paper, an attempt has been made to document the available primary REE deposits of our country and emphasize the need to prioritise secondary deposits considering their wide occurrence, simpler extraction approaches and lower environmental challenges. Though secondary deposits such as ion adsorption clays, regolith developed over granitic/alkaline rocks, sedimentary phosphorites, as well as mine, industrial and e-waste are low grade, their ready availability may help meet the immediate REE demand of our country. These secondary resources are not only alternative sources, but may also become the emerging frontiers for REE exploration in the future.

***Keywords**: Rare earth elements (REE), Primary deposits, Secondary deposits, REE mobilization, Deposition*

1. Introduction

Rare earth elements (REE), occurring as a coherent group due to their unique chemical properties, are not truly rare but exist in all the rock types, displaying systematic fractionation from Lanthanum to Lutetium (Rollinson, 1993). They are crucial for deciphering the mantle and crustal processes, providing valuable insights on the petrogenesis of igneous rocks, and depositional conditions of sedimentary rocks. In metamorphic rocks, REE serve as excellent geochemical tracers for estimating the pressure-temperature conditions, metamorphic reactions and inferring the parent rock composition (Shatsky et al., 1990). Over the years, these elements have been extensively utilized to unravel Earth's internal and external processes. However, with the ongoing global transition towards green energy combined with geopolitical issues and our country's efforts towards self-sustainability, there is an urgent need to secure reliable REE supplies. Although primary REE deposits remain the highest priority, they alone may not be able to meet the rising national demand (Balaram, 2019, 2023). Their distribution is limited to a few countries, and mining them involves complex and environmentally challenging processes, which brings a compelling opportunity to search for alternative resources. Keeping in view of the growing REE demand, it is essential to concentrate on secondary REE deposits, which remain underexplored yet offer simpler extraction procedures, economic viability and fewer environmental challenges (Balaram, 2023). In this paper, while highlighting the occurrence of selected primary and secondary REE resources from literature, an attempt has

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been made to emphasize the necessity to look beyond the primary sources and explore the underexplored secondary resources such as ion adsorption clays, weathered regoliths, sedimentary phosphorites, supergene Mn ore etc. These secondary resources are not merely alternatives, but with appropriate technological advancements, they represent emerging frontiers for future REE exploration and exploitation.

2. An overview of REE Resources

As REE have become essential in terms of energy efficiency, environmental protection and advancing digital technology, nations are focusing on securing REE resources, which is also influenced by the geopolitical decisions that lead to supply chain disruptions and imbalance in production and demand. Considering the economic importance, supply-risk and few other parameters such as disruption potential, substitutability, cross cutting usages along different sectors, import reliance and recycling rates, Indian government has adopted a critical mineral strategy identifying 30 commodities which includes Sb, Be, Bi, Co, Cu, Ga, Ge, graphite, Hf, In, Li, Mo, Nb, Ni, PGE, P, potash, REE, Re, Si, Sr, Ta, Te, Sn, Ti, W, V, Zr, Se and Cd. The policy decisions in the mining sector of various countries are reframed by increasing the royalties of a few critical minerals to boost mining and domestic production. In this direction, the Government of India recently promoted the auction of Cs, Rb, Zr and graphite mineral blocks, considering their associated mineral assemblages such as Li, REE, W and Nb by increasing the royalty rates by 2% on the average selling price. According to USGS Mineral commodity summaries (2025), the global REE reserves exceed 90 million tonnes, of which India is reported to contain about 6.9 million tonnes contributing ~7.6%. Other contributors include Australia (6.3%), U.S. (2.1%), Brazil (23.3%), Madagascar (7.6%), Russia (4.2%), Vietnam (3.9%), with China being the leading producer, hosting ~48.8% of the reserves. The Indian sub-continent, with its diverse geological and tectonic environments with long coastlines on both the west and east, Precambrian crustal blocks, Proterozoic basins and mobile belts, along with Neo-tectonic Himalayan orogen offers huge potential for REE resources. These occur as beach and inland stream placers, carbonatites, peralkaline to alkaline felsic rocks, pegmatites, shear zone hosted deposits, quartz pebble conglomerates (QPC), bauxite, laterite, phosphorites, ion adsorption clays, Fe-Mn breccia/laterite etc.

With the increase of atomic number (57-71), the concentration of REE decreases, following the Oddo-Harkins effect in this continuous sequence of elements. Among them, even atomic numbered elements are generally more abundant compared to odd atomic numbered elements. Therefore, Ce is relatively abundant (~63 ppm) and Lu is low (0.4 ppm) in the Earth's crust (total REE=169.1 ppm), and LREE are abundant (137.8 ppm) compared to HREE (31.3 ppm; (Rudnick and Gao, 2003). The tendency of these elements to occur in solid solution at low concentrations, rather than in pure mineral phases, makes them rare earth elements (Haxel et al., 2002). Major REE bearing mineral phases include oxides, carbonates, halides and phosphates (Jordens et al., 2013; Dushyantha et al., 2020), among them monazite, xenotime and bastnasite are significant in holding major REE resources (Jha et al., 2016; Meshram and Pandey, 2019). Monazite and bastnäsite predominantly host LREEs, whereas monazite consist of lower La, higher Nd contents along with HREEs. Besides, monazite contains the radioactive elements thorium (Th) and uranium (U) (Andreoli et al., 1994; Hussain et al., 2020; Su et al., 2021; Dostal and Gerel, 2023). Xenotime is characterized by the HREEs (such as Y, Dy, Er, Yb, and Ho; Harben, 2002). Indian monazite is different from that of China with respect to their Th and U contents (Xu et al., 2022). Though there are different ways of classification of REE deposits, primary deposits are formed by igneous and hydrothermal processes, and secondary deposits are formed through weathering and sedimentary processes. In India, the major source of REE is from secondary deposits (beach sands). Carbonatites and alkaline igneous complexes, pegmatites and magmatic hydrothermal deposits form the primary deposits. Carbonatites constitute the most significant REE resource globally, with 5-15% REO (Wall and Zaitsev, 2004; Verplanck and Van Gosen, 2011; Singh, 2021), commonly occurring in stable regions (cratons), associated with alkaline silicate rocks and varying in composition from calcic, ferro-carbonate to dolomitic or sideritic (Schulz et al., 2017; Simandl and Paradis, 2018; Pirajno and Yu, 2022).

2.1. Primary Deposits

Amba Dongar Carbonatite Complex (ADCC), Siriwasan Nakal carbonatite, Panwad Kawant carbonatite of Chhota Udaipur district, Gujarat; Kamthai Carbonatite Complex (KCC), Barmer District; Mer-Mundwara carbonatite of Sirohi district, Rajasthan; Niwania carbonatites of Udaipur district, Rajasthan; Samchampi carbonatites, Barpung carbonatites, Mikir Hills, Jasra carbonatites of Karbi Anglong district, Assam; Sung valley carbonatites, Jaintia Hills district Samalpatti, Sevattur carbonatite massifs and associated alkaline complexes in Tamil Nadu are promising REE resources (Fig. 1; Singh, 2020). Besides, the highest total REE content (up to 3%) has been reported in the benstonite carbonatites and apatite-magnetite bands of Jogipatti carbonatites of Tamil Nadu. The Pakkanadu-Mulakkadu carbonatites of Salem district are associated with pyroxenites and intruded by syenites, consisting of large bastnasite, monazite crystals; cerianite, allanite and other heavy minerals (barite, apatite, magnetite, zircon, etc.), and reported to contain 5.83% TREE (Fig. 1; Balasubramanian et al., 2017). Sevattur carbonatites of Tamil Nadu with higher REE content are significant with the occurrence of uranopyrochlore which contains TREE up to 1.78% (Borodin et al., 1971; Singh, 2020). Apart from this, carbonatites present as small outcrops in Tirupattur, Sundarampalli, Kudumandapatti, Todakullanur and Dindigal of Tamil Nadu, reported to contain allanite which display higher REE oxides. The Khamambettu carbonatites of Tamil Nadu are hydrothermal type containing monazite, barite, strontianite, celestine mineral assemblages (Burtseva et al., 2013). The deformed carbonatite body of Elchuru, Prakasam district, Andhra Pradesh are associated with nepheline syenites (Leelanandam et al., 2006; Kumar and Leelanandam, 2008) which contain TREE of 252 ppm and require further investigations. Dacherla syenites of Ananthapur district, Andhra Pradesh are reported to contain moderate REE contents (Arif and Raju, 2019). Beldih-Kutni carbonatites of West Bengal consist of alkaline-carbonatite complex with alkali pyroxenite, nepheline syenite, phoscorite, carbonatite, syenitic fenite and glimmerite reported to contain REE and Nb mineralization.

The alkaline-peralkaline felsic rocks, such as granite, rhyolite, syenite etc. have been explored for REE and rare metal (RM) globally due to their emplacement in anorogenic tectonic settings related to rifting. The peralkaline anorogenic granites have enrichment of MREE (Sm, Gd, Tb, Dy), whereas peralkaline granites and associated volcanics display enrichment in rare metals, attributed to volatiles dissolved by the peralkaline melts, which form complexes that keep REE and HFSE mobile. Though some minerals crystallise, they remove little of these elements. Therefore, the melt becomes progressively enriched in REE, Th, U and HFSE. In India, the Siwana Ring Complex (SRC) of Barmer District, Rajasthan, is reported to have significant REE mineralisation in peralkaline granitoids, rhyolitic tuffs, fine-grained granites, and microgranites, which are present as dykes. Atomic Minerals Directorate (AMD) results speculated more than one million tonnes of reserves in this area. Significant concentration of REEs has been reported from Golia-Gungrot, Mailawas, pink granites of Mamaji-ka-Wala, granite dykes of Ludhrara, Ramaniya and Indrana areas, fine grained granites of Gudanal and Meli, micrugranites of Bhatikhera, Phulan and Nal, tuffaceous rhyolites of Dantala, fine grained granite dykes of Mokalsar, rhyolites of Mawri, Sheetala Mata. Among them, Gudanal, Nal, Dantala, Bhatikhere, Meli and Phulan contain high HREE and Y resources. Sarnu Dandali alkaline complex contains high Nb and moderate REE abundance. Granites from the Kundal area and the

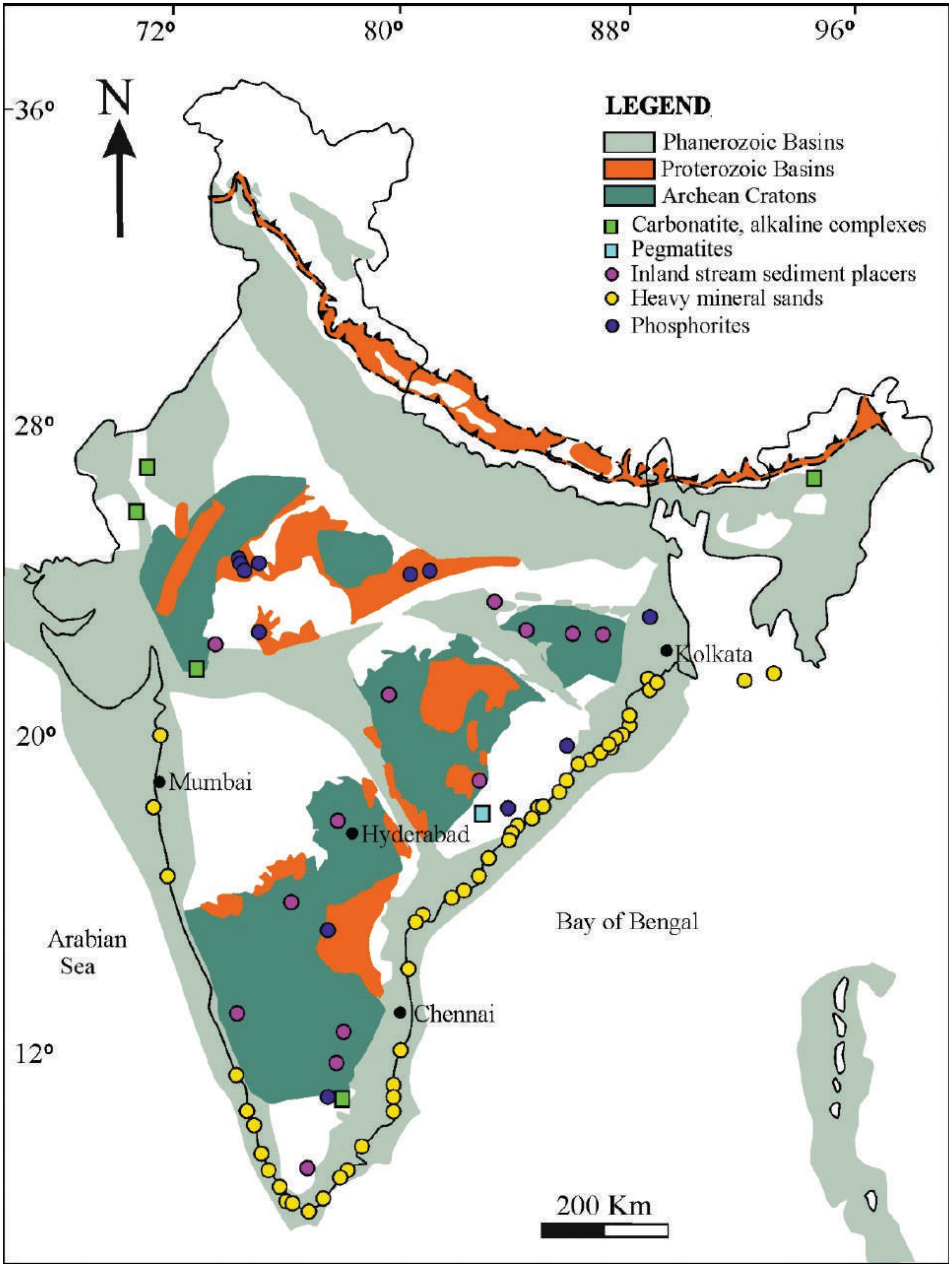

Fig. 1: Map showing the distribution of REE resources within the cratons and sedimentary basins in India *(modified after Sengupta and Van Gosen, 2016; Chakraborty et al., 2019, 2020; Singh, 2020).*

Nakora Ring complex, Barmer district, Rajasthan, consist of high Zr, Y and REE (Singh, 2020). The rhyolitic dykes from Dhorio Nes, Jamnagar district; felsic igneous complex of Alech Hills, Jamnagar, Gujarat; granites of Sudasna area and ringuaite dyke from Gir forest, Gujarat contain higher concentrations of REE. Furthermore, granites from Kinwat, Maharashtra, Dongargarh, Chhattisgarh; Kanigiri, Andhra Pradesh; Pala Lahara and Kumarkunti-Jharnomal, Odisha; Kuilapal, West Bengal; Nongpoh, Meghalaya; Karbi Hills, Assam are also reported to contain anomalously high REE (Singh, 2020). Hydrothermal vein-related mineralisation is present as apatite-magnetite veins in the Singhbhum shear zone, South Purulia shear zone, within the charnockites of Kasipatnam, Vishakhapatnam, the albitite belt of western India, Rajasthan and Haryana. The U-mineralized Gogi limestone and its basement granite from Bhima basin, Karnataka are reported to contain high REE and Y (Singh, 2020), and it is suggested that REE may be recovered as a by-product. U-mineralization has been identified in most of the Proterozoic sedimentary basins of India, including Kalagdi, Chhattissgarh, Bijawar, Vindhyan, Abujhmar, Indravathi etc. which shows hydrothermal vein type mineralization (Nanda, 2016; Singh, 2020).

REE bearing Pegmatites have been reported from Kotwalpara, Challanpara, Metapal, Hatpasrapara of Bastar and Tappa, Mahasamund district, Chhattisgarh; Pandikimal, Jharsuguda district, Sahaspur, Kuladera, Tora, Rerakhol of Sambalpur district, Angul district of Odisha; Selaya, Belangi of Sarguja district of Chhotanagpur granite gneiss complex; Jaurahi, Lekhar, Kanwah, Nawatola, Rajon, Kudri and Anjangira from Sonbhadra district of Uttar Pradesh (Singh and Sharma, 1997; Kumar et al., 2000; Dhurandhar et al., 2003; Sengupta et al., 2006; Singh and Viswanathan, 2011, 2015; Singh, 2020); Singar and Pichhli of Gaya district, Bihar; Nirupahari and Khairidih of Koderma district, Bahea-Ulathu-suratoli and Karmatoli of Ranchi district, Goriadih, Bhalmanua, Doranda, Bangaikalan of Hazaribagh district, Amarjharna and Dabur districts of Jharkhand (Ramachandran and Sinha, 1992; Singh and Viswanatha, 2015). Pegmatites consisting of bastnasite-allanite have been traced intermittently over an area of 20 km at Ukma, Nawahatu, Timangda and Gunja areas from North Purulia shear zone, Purulia district of West Bengal (Basu and Ghosh, 1999; Sinha, 1999). Pegmatites of Rajasthan are present in Modiya, Pisangan, Almada-Devpura, Danta-Bhunas of Ajmer, Bhilwara district, Phalwada-Positara of Sirohi district, Siwana, Ludhrerara of Barmer district, Sundarchar and Kankroli of Rajsamand district, Ghalwalo and Goga temple of Jhunjhunu district, Noornagar of Alwar district, Bhagwanpura of Sikar district, Rajasthan. In Gujarat, pegmatites containing REE minerals are reported from Idar, Umedpur in Sabarkantha district, Surda-Dhanpura in Banaskantha district, and the Palanpur region. REE bearing minerals are identified in the pegmatites of Lawadia, Bhandara district, Chapegharhi of Nagpur district, Aheri of Chandrapur district, Mosam of Gadchiroli district, Khatgare-Shapur of Nanded district of Maharashtra. REE bearing pegmatites are reported from Amaravaram, Nalgonda district, Telangana; and Parlapalle, Kattubadipally, Annavaram, Giddalur, Jogipalle, Tadpatri, Sankara mine of Nellore district of Andhra Pradesh (Krishna and Thirupathi, 1999; Singh and Viswanathan, 2015; Viswanathan et al., 2015; Singh et al., 2015; Reddy et al., 2015). REE and RM bearing pegmatites are present in Mandya, Yadgiri, North Canara and Bangalore districts of Karnataka (Krishna and Thirupathi, 1999; Singh and Viswanathan, 2015; Singh, 2020). In Tamil Nadu, Vellore, Karur, Salem, North Arcot, Nilgiri, Tiruchinapalli, Coimbatore, and Madhura districts contain REE and RM-bearing pegmatites. In Kerala, the pegmatites of Sandiremalai in Palghat district, pegmatites at Kalkulam contain REE bearing mineral phases (Sarkar et al., 1990). Published data indicate that pegmatites of our country have abundant REE and RM potential along with multiple metal oxides which requires a suitable metallurgical process to recover them.

2.2. Secondary REE deposits

Secondary REE deposits are formed by secondary processes through weathering and erosion. They are placer deposits, Fe-Mn supergene ore, bauxite, phosphorites/phosphatic sediments, lateritic cover over alkaline rocks, ion adsorption clays, etc. Coal fly ash, ocean bottom sediments, and mine dumps, some industrial waste can also be categorised under the secondary deposits (Balaram, 2023). The placer deposits are formed due to detrital weathering, transportation and deposition, whereas the supergene ore is the product of chemical weathering. The Ion adsorption clays are the product of in-situ weathering. Unlike primary deposits, secondary deposits are difficult to identify, as there are many factors which control the deposition of REE or Rare Metals (RM) in them. In general, Tertiary and Quaternary coastal deposits are REE-bearing globally (Oris and Grauch, 2002), which predominantly consist of monazite and xenotime.

2.2.1. Placer Deposits

Placer deposits have also been referred to in the literature as secondary deposits, beach deposits, and Heavy Mineral deposits (HMS), given the enrichment of REE in high specific gravity minerals (~2.9 g/cm^3; Perks and Mudd, 2019; Subasinghe et al., 2022; Morin-ka et al., 2025). Irrespective of our meagre contribution to the global REE output (72%; USGS, 2024; van Gosen et al., 2014), India occupies first position in extracting rare earths from placer deposits. Heavy mineral species are predominantly silicates, oxides, phosphates, sulphides and sulphates, which include monazite, xenotime, garnet, zircon, rutile, ilmenite, etc. Leucoxene is an alteration product of ilmenite and rutile, which is a source for titanium, while zircon provides zirconium. The main source of REE in these deposits is monazite and xenotime (Mudd and Jowitt, 2016).

Placer deposits are present in continental shelves, medium to fine grained, well sorted, usually unconsolidated and range from a few kms. to tens of kilometres in length and tens of meters width (Fig. 1; Force, 1991; Hou et al., 2011; Singh, 2020). Placer deposits are upgraded through transgression-regression cycles and thorough reworking (Hou et al., 2006, 2008, 2011). A recent study by Morin-ka et al. (2025) indicates that out of 1173 global placer deposits, 945 deposits are occupied in more than 45 countries with an additional 228 new reports. The Indian placer deposits for REE are reported to occur in Kerala, Tamil Nadu, Odisha and Andhra Pradesh. The placer deposits of Odisha are distributed in its southern sectors. The number of REE deposits in Andhra Pradesh is higher in the northern sector, which occurs at Bhavanapadu, Kalingapatnam, Srikurmam, Bhimunipatnam, Koyyam, Donkuru-Barua and Kandivalasa areas, with considerable variation in their total REE. The central sector deposits are situated in Kakinada, Nizampatnam and other areas whereas, the northern sector deposits are situated along Peleru (Singh, 2020). The Manavalakurichi sector of Tamil Nadu consists of a large REE deposit of Kollamkode-Vayakkallur, Thengapattanam-Kolachal, Kolachal-Manavalakurichi (MK Deposit), Pillaithoppu-Manakadu, Kanyakumari-Kuttupulli whereas the Ovari sector contains Navaladi-Tiruchendur deposit. Besides, Navaladi-Tiruchendur deposit of Ovari sector, Tiruchender-Tondi deposit of Tuticorian sector, Vellanganni-Cuddalore deposits of Karaikal sector and Pudupattanam-Kalpakkam deposits of Kalpakkam also produce REE in Tamil Nadu (Singh, 2020). In the state of Kerala, the Chavara deposit has northern continuity at Kayamkulambar-Arattupuzha, the NTPC plant, Arattupuzha-Thrikunnapuzha, and Thrikunnapuzha-Thotapalli. Apart from this, there are onshore land, lake and sea bed resources which are known as Barrier beach, its eastern extension, northern and southern sectors; Kayamkulam lake bed, Vatta estuary, Ashtamudi lake, Neendakara-Kayakulam sea bed (Krishnan et al., 2001; Singh, 2020). The Ratnagiri district of Maharastra contain heavy mineral deposits at Purangad, Gaonkhede, Randapar, Bhatya, Ratnagiri, Kalbadevi, Newre and Malgund, which range from monomineralic (ilmenite) to bi-mineralic (ilmenite and magnetite) and are devoid of monazite, zircon and garnet due to the Deccan basalt source of these deposits (Ali et al., 2001; Singh, 2020).

Though the Narmada River estuary at the Gujarat coast is reported to contain monazite, studies are limited. According to Mallik and Sensarma (2009), the stream and beach placers of West Bengal are inconsistent, they are not economically viable for mining.

2.2.2. Inland stream placer deposits

In addition to beach placers, which are LREE-rich, inland placer deposits are also significant, with high potential for HREE and Y contents (Fig. 1). The Chhotanagpur Granite Gneiss Complex (CGGC) present in West Bengal, Bihar, Jharkhand, Uttar Pradesh, Madhya Pradesh and Odisha is exceptionally promising with the enrichment of both LREE and HREE along with Y contents. The Ranchi-Purulia belt of Jharkhand and West Bengal; Deo, Girma, Halwai, and Pojenga river placers from Simdega district of Jharkhand are rich in REE (Rai et al., 1991; Singh and Rai, 2008). The Siri-Champajharia, Baljora river sediments of Jashpur district, Chhattisgarh, have extensive REE placers (Singh et al., 1996). REE, U, and Th mineralisation with the presence of xenotime-bearing placers has been reported from a large number of streams, including the Mahan and Kanhar rivers, which drain the Precambrian rocks situated in the Jajawal-Dumhat-Dhabi-Paraswar-Balrampur areas of Chhattisgarh and Uttar Pradesh (Singh et al., 1999; Singh, 2020). The Jhiram, Dumam, Mari, Kawara and Nakti rivers of Chhattisgarh and Dussanada stream placers of Odisha, belonging to the Bastar terrain, granitic soils of Hassan, Mandya and Raichur districts of Karnataka, belonging to Dharwar Craton; Goddaru Vanka stream and granitic soils in the Kullampati area in North Arcot district and Salem district, belonging to Southern Granulite Terrain, are also reported to contain rare earth elements (Singh, 2020). Kameng river stream sediments of Arunachal Pradesh and granitic soil, Garo Hills, Meghalaya, are reported with U, Th and REE enrichment (Singh, 2020). It is suggested that the younger potassic granites, alkaline granites and associated soils and quartz veins of the Dharwar Craton may also be promising lithounits for potential REE resources (Singh, 2020).

2.2.3. Phosphorite deposits

In India, low grade sedimentary phosphorite deposits occur in the Aravalli phosphogenic province and the Paleozoic basins of extra peninsular India, such as Mussoorie syncline (Fig. 1). However, they exhibit low REE contents of below the economically viable threshold. In contrast, the phosphatic bands within the Owk shale formation of Kurnool Group are reported to be enriched in REE up to 1,200 ppm (Harshitha et al., 2026). In addition, the silico-phosphatic rocks associated with radioactive quartz reef in the Proterozoic Bijawar basin have an average of 0.47% of rare earth oxides, whereas the phosphatic sandstone from Dai-Amarpura, phosphatic shale from Bassai and phosphatic breccia from Hirapur are reported to contain ~0.45% rare earth oxides (Roy et al., 2014). The REE-bearing phosphorus is suggested to be redox sensitive and, in general, correlates with uranium (Harshitha et al., 2026). The uraniferous phosphatic rocks of Bhima, Chattisgarh and Vindhyan basins may be evaluated for possible REE potential. The igneous phosphorites, which contain high phosphorus, are being utilised for manufacturing phosphoric acid, and the byproducts are suggested to contain higher REE contents of ~0.4% which may serve as a potential secondary resource and need detailed investigations (Singh, 2020).

2.2.4. Ion adsorption clays & Regolith

These clays form under humid climate (sub-tropical to tropical conditions) associated with intense and prolonged weathering of a REE rich source rocks such as granites, alkaline granites and few types of volcanic rocks. The climatic conditions promote chemical weathering, break the REE bearing minerals from the source rock and release these elements which migrate through water and get adsorbed to the clay minerals that have high surface area (kaolinite, smectite etc.). Variation in oxygen levels and pH conditions influence the REE adsorption and separation of LREE and HREE. Gentle topography (low altitude) prevents removal of REE and promotes the development of a thick regolith, which traps the adsorbed ions. In India, the weathered horizons occurring within the Nongpoh granite, situated within the Shillong series of the Meghalaya plateau, are REE-enriched (Sadiq et al., 2014). Several granitoid batholiths of Shillong plateau such as Kyrdem, Mylliem, South Khasi, Rongjeng, Sindhuli etc. are under study to identify their REE potential (Krishnamurthy, 2024). The unconsolidated weathered material above the bed rock such as granites, alkaline rocks, which are rich in REE, are generally considered regolith, which will have different layers of soil with gravel and bedrock. Geological Survey of India has identified regolith-type REE resources in the granitic and gneissic rocks of the Sausar belt, Central India (Krishnamurthy, 2024). The regolith present within the alkaline granites from different parts of our country needs to be assessed for its REE potential. The existing clay resources at Kerala, West Bengal, Rajasthan, Odisha and Karnataka have vast clay deposits that need detailed studies. Though a large number of studies are going on for the evaluation of REE potential, the Ion adsorption clays and regolith remain the least explored. The exploitation of these low-grade deposits may be economically cheaper and environmentally less challenging and hence need detailed investigations on priority basis to meet the REE demand of our country.

2.2.5. Other possible resources

Mn ore is formed when the proto-ore, such as Fe-Mn arenite or argillite, undergoes weathering under oxidizing conditions. The metals dissolve, migrate downward with groundwater, and re-precipitate to form Mn-rich ore. In the Dharwar Craton, the Mn-ore is hosted as lensoid/pocket type ore within clays. These Mn oxides and oxyhydroxides such as birnessite, cryptomelane, and todorokite possess high surface area and strong adsorption capacity. Although they may be economically low grade for primary mining, they can still serve as valuable by-products. In addition, red mud, coal fly ash, industrial waste, mine tailings/slags, and recycled electronic waste may also be considered as potential REE sources, provided that suitable extraction methodologies are developed to meet the growing REE requirement of our country (Balaram, 2023).

3. Geological factors influencing REE transit from source to sink in secondary deposits

3.1. REE mobilization (Source rock to fluid)

3.1.1. Source rock geochemistry

The secondary REE deposits viz. ion adsorption clays, heavy mineral sands and placer concentrations derive REE through weathering, dissolution and mineral breakdown primarily from granitic source rocks owing to their crustal abundance, which on an average contain a total REE content of 268 ppm (Krauskopf and Bird, 1995). Although the release of REE into the weathering-transport system is mainly attributed to the alteration of feldspars and micaceous minerals into clays, which adsorb REE released through the breakdown of accessory phases, the main controlling factor is their mineral heterogeneity and their contrasting weathering kinetics. The degree to which each of the mineral group is susceptible to weathering controls both the timing and magnitude of REE liberation. For example, easily altered phosphates and silicates such as apatite and allanite release LREE and MREE initially in the weathering sequence, whereas, resistant phases such as xenotime and zircon delay HREE release (Li et al., 2017), therefore regulating the temporal and spatial REE fractionation during their transport.

Deposits formed through authigenic enrichment such as phosphorites, Fe-Mn nodules and marine carbonate ooids concentrate REE through seawater precipitation and subsequent mineral adsorption/surface complexation during diagenesis. These impart characteristic seawater REE signatures including MREE enrichment in phosphatic minerals, positive Ce and negative Y anomalies in Fe-Mn phases and elevated Y/Ho in carbonates. During early diagenesis, REE can be redistributed through apatite recrystallisation, redox-sensitive uptake of Fe-Mn oxides, as well as microbially mediated mineral transformations, resulting in localized

REE enrichment, independent of detrital supply (Ohta and Kawabe, 2001; Yang et al., 2024; Harshitha et al., 2026). However, the REE inventory of the seawater, and consequently the authigenic deposits is ultimately sustained by continental weathering and terrigenous influx which supply dissolved and particle-bound REE to the marine system as part of the broader geochemical cycle (Pourret and Tuduri, 2017).

3.1.2. Rock weathering and hydrothermal alteration

The weathering and hydrothermal alteration processes are major controls on the initial mobilization of REE from source rock into circulating fluids. Chemical weathering breaks down minerals such as apatite, monazite, allanite etc. releasing REE into pore waters, typically in acidic, oxidizing environments which favor the maximal dissolution (Sergeev and Collins, 2024). In regolith hosted deposits, as weathering profile is developed as weathering progresses, with the lowermost horizon comprising unweathered basement rock, which transitions into weakly weathered bedrock zone- saprock (saprolite), mottled zone and then a residuum of ferruginous, clayey or siliceous horizons, followed by organic, humus rich soil at the surface (Russo et al., 2025 and references therein). In this profile, REE enrichment is typically concentrated within the clay-rich residual horizon where ion-adsorption processes dominate. However, not every weathered profile can contribute to the formation of regolith hosted REE mineralization, as REE are most commonly concentrated in insoluble minerals such as monazite and xenotime in the parent granitic rocks, resulting in the formation of heavy mineral sands (Wall, 2020). When high grade metamorphic or igneous rocks rich in these REE-bearing heavy minerals are weathered by groundwaters, humic acids and other intrabasinal fluids, they produce the detritus of sand, silt, and clays that is transported by fluvial systems towards coastal environments. Hydrodynamic sorting concentrates the dense mineral grains, forming laminated or lens-shaped heavy-mineral-rich sand bodies, the most economic of which occur in Paleogene to Quaternary deposits (Van Gosen et al., 2014).

In contrast to weathering, which principally acts to break down source minerals, hydrothermal alteration contributes to enriching the REE contents in the source rock by precipitating secondary REE-carbonates and phosphate phases such as rhabdophane, fluorapatite, bastnäsite, cerianite, florencite etc. (Sanematsu and Watanabe, 2016). As hydrothermal alteration processes such as greisenization, carbonatization etc. destabilize primary accessory minerals liberating REE, subsequent cooling or mixing of fluids allow the reprecipitation of these secondary REE phases (Fig. 2; Upadhyay et al., 2021; Knorsh et al., 2024.)

3.1.3. Percolating fluid chemistry (pH, Eh)

REE are generally immobile in most crustal environments, but their solubility increases significantly when fluids attain certain conditions that stabilize REE-bearing complexes. Experimental investigations on REE speciation in simulated and natural fluid compositions over different ranges of pH, temperature and pressure were carried out by several workers, which ultimately suggest that acidic and oxidizing conditions favor maximal leaching of REE from source rocks, as they form stable chloride and sulfate complexes in such environments. However, within the most commonly present chloride-rich hydrothermal fluids, REE transport is facilitated by the formation of simple hydrated cation complexes with sulphate and fluoride under acidic conditions (pH<~5.5), and carbonate, phosphate, hydroxide complexes under circumneutral (pH ~5.5-7.2), and alkaline conditions (pH>7.2; Fig. 2; Wood, 1990; Johannesson et al., 2000; Lozano et al., 2019).

Redox potential (Eh) also controls REE mobilization by influencing the stability and dissolution of complexing ligands and redox sensitive host phases such as Fe-Mn oxyhydroxides, organic matter and sulfides. Under oxidizing conditions, REE are efficiently scavenged onto Fe-Mn oxyhydroxides and particulate organic matter, whereas reducing conditions destabilize

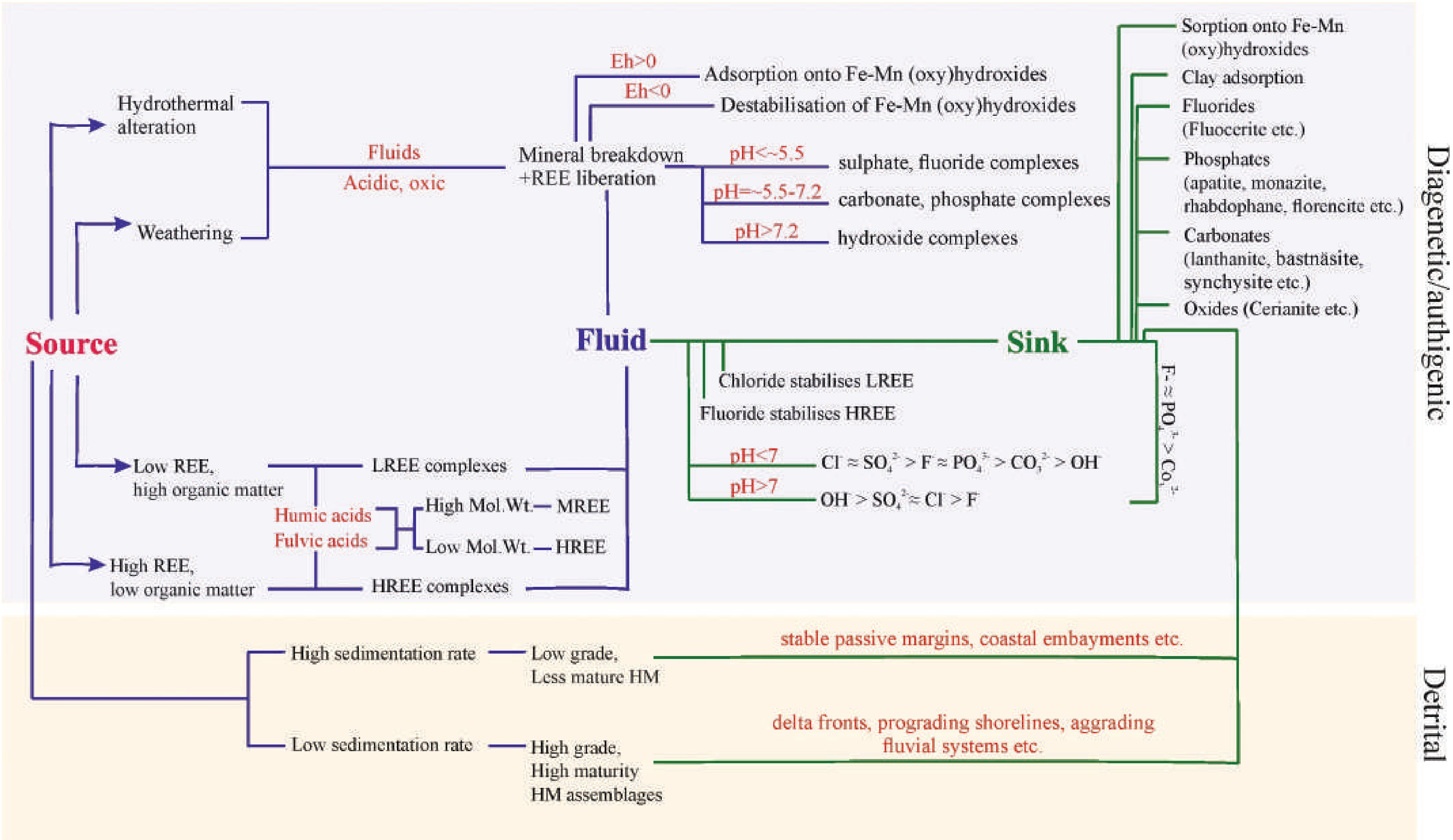

Fig. 2: Illustration depicting the conceptual summary of geological, geochemical, and sedimentary factors controlling REE transfer from source to sink through fluid pathways in detrital and diagenetic environments

these phases, releasing previously adsorbed or coprecipitated REE back into solution (e.g., Ohta and Kawabe, 2001; Johannesson et al., 2004; Arienzo et al., 2022; Fig. 2).

3.1.4. Complexing ligands (CO_3^{2-}, F^-, Cl^-, SO_4^{2-}, organic acids)

According to Pearson's hard-soft acid-base concept, REE behave as hard acids and preferentially bind to basic ligands such as F^-, SO_2^{-4}, CO_2^{-3}, PO_3^{-4} (Pearson, 1963). However, most of the REE resist hydrolysis at ambient temperatures and therefore occur mainly as free or hydrated ions in low-T acidic to weakly alkaline fluids, except Sc which shows greater tendency to hydrolyze. As REE are leached from melts or minerals by percolating hydrothermal fluids or groundwater, they become stabilized and transported in solution by complexing with available ligands. With the increasing abundance of ligands in percolating fluids, REE are transported in the general order of $Cl^- \approx SO_4^{2-} > F^- \approx PO_4^{3-} > CO_3^{2-} > OH^-$ under acidic conditions, and $OH^- > SO_4^{2-} \approx Cl^- > F^-$ under alkaline conditions (Migdisov et al., 2009; Wan et al., 2023). In acidic to near-neutral conditions, SO_4^{2-} and Cl- complexes favor REE transport, while F- H≈ $PO_4^{3-} > CO_3^{2-}$ promote REE deposition. Furthermore, ligand selectivity also varies, with fluoride stabilizing HREE complexes more effectively, while chloride preferentially complexing with LREE (Fig. 2; Migdisov et al., 2016). Collectively, conditions of high temperature, low pH, abundant ligand concentrations and high salinity is considered to favor maximal REE dissolution and transport in hydrothermal fluids (Di and Ding, 2024).

3.1.5. Organic matter interaction and microbial mediation

Apart from the inorganic complexes (humic substances, HS) discussed above, organic ligands, mainly humic and fulvic acids play an important role in REE complexation in organic-rich groundwaters (Tang and Johannesson, 2003). REE complexation with humic substances generates characteristic fractionation patterns, where low REE and high organic matter conditions favour HREE complexes, while higher REE and lower organic matter conditions preferentially stabilize MREE (Marsac et al., 2008; Stern et al., 2007). Molecular weight further influences fractionation, with high molecular weight humic acids binding MREE more strongly and low molecular weight fulvic acids favouring HREE (Fig. 2; Sonke and Salters, 2006). pH further controls both HS solubility and competition with inorganic ligands such as CO_3^{2-}, which dominate REE complexation in fluids with low organic matter (Tang and Johannesson, 2010). Additionally, elevated Fe and Al further inhibit REE-HS binding. Thus, organic ligands are important REE carriers in organic-rich settings, particularly river waters and regolith over granitic or alkaline rock bodies where root and microbial activity is prevalent in tropical to subtropical regions.

In diagenetic REE resources such as phosphorites, microbial mediation is often considered to play an important role in REE enrichment. For example, in the Zhijin Motianchong and Meishucun phosphorite deposits of China, organic, inorganic $\delta^{13}C_{carb}$ data and total organic carbon contents indicated that REE+Y were released into porewaters due to anaerobic oxidation of organic matter at the sediment-seawater interface, resulting in the REE enrichment of Zhijin phosphorites (Wu et al., 2022). Similarly, in the phosphorites of Cuddapah basin, India, pronounced MREE enrichment has been attributed to the MREE scavenging by Mn-(oxy) hydroxides and organic matter, supported by the presence of Ediacaran microfossils and fossiliferous pyrite (Fig. 3; Harshitha et al., 2026). A comparable mechanism is reported from the Kuh-e-Sefid phosphorites of Iran, where hydrocarbon rich components provided functional groups capable of binding, and stabilizing REE complexes, thereby enhancing REE enrichment under dysoxic to anoxic conditions (Zarasvandi et al., 2019). Together, these studies indicate that mineral-organic interactions significantly influence REE distribution and enrichment in diagenetic systems.

3.2. REE deposition (Fluid to sink)

3.2.1. Precipitation as phosphates, carbonates, fluorides

In low temperature surface environments, REE precipitation from fluids occurs mainly through variations in porewater, sea- or meteoric water chemistry, and occasionally from low-T hydrothermal fluids such as in weathered carbonatites or fault-controlled basins. As REE-bearing fluids migrate through sedimentary basins, soil or regolith, precipitation occurs as a result of changing solubility caused by changing temperature, pressure, redox state or fluid composition, forming secondary REE phosphates (apatite, monazite, rhabdophane, florencite etc.), carbonates (lanthanite, bastnäsite, synchysite), oxides (cerianite), or rare fluoride rich minerals (fluocerite). Phosphate precipitation is most widespread in marine and diagenetic environments, as REE+Y readily substitute into the crystal lattice of carbonate-fluorapatite during early diagenesis. Recrystallization of biogenic apatite and the formation of authigenic phosphatic nodules or coatings can further concentrate REE.

In regolith and weathered profiles, REE accumulation occurs either through the adsorption of dissolved REE ions onto clay mineral surfaces or through precipitation of insoluble REE-phases (Borst et al., 2020; Wu et al., 2023). Secondary phosphates such as rhabdophane may precipitate from acidic and REE-rich porewaters, as the dissolution of abundant primary P-rich phases increases dissolved phosphate content, which then acts as a depositional ligand capable of outcompeting the fluid acidity and thereby inducing REE precipitation (Bamforth et al., 2024). Secondary carbonate precipitation can occur in alkaline conditions where high bicarbonate contents promote the formation of amorphous REE-carbonates or poorly crystalline rhabdophane like phases which often act as transient REE hosts prior to further diagenetic enrichment (eg., Wang et al., 2024). Fluoride-rich REE minerals are less common in secondary environments but may form locally as fluoro-carbonate phases where fluorine is released during weathering of granites, carbonatites, or apatite-rich sediments, forming low-T REE-fluoride or mixed fluoride-carbonate phases (eg., Yang et al., 2023).

3.2.2. Sorption onto clays and Fe-Mn (oxy)hydroxides

REE sorption onto clay minerals is the main process behind the formation of ion adsorption clay

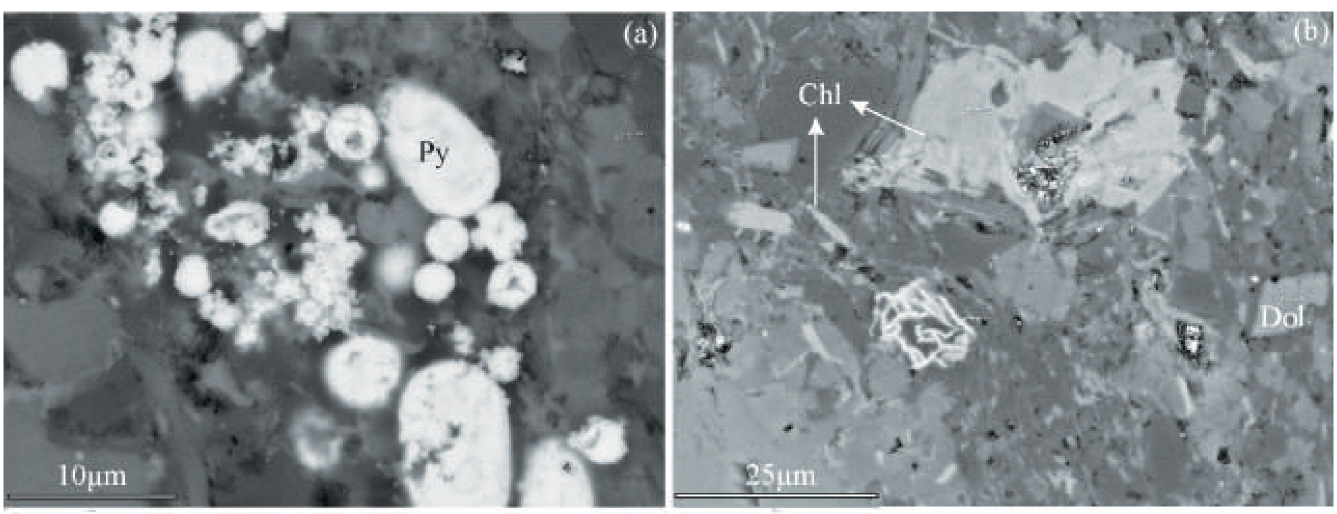

Fig. 3: BSE images showing (a) fossiliferous pyrite occurring as framboidal to irregular aggregates and (b) filamentous structure preserved within the Ediacaran phosphorites of the Cuddapah Basin. EDS spectra from the filament revealed enrichment in Ti and Si, with minor amounts of Al, Fe, and Ba, interpreted as secondary mineral infilling of an original biological filament.

deposits, where REE from the percolating fluids are adsorbed onto clay mineral surfaces. 1:1 clays such as kaolinite and halloysite are the most common REE hosts, although 2:1 clays viz. smectite, vermiculite and illite may also be present within these deposits. The adsorption capacity of these minerals is controlled by their physicochemical surface properties such as surface charge, specific surface area (SSA) and cation exchange capacity (CEC; Coppin et al., 2002). Due to the presence of hydrated interlayered and extensive isomorphic substitution, 2:1 clays generally exhibit higher SSA, surface charges, greater CEC and therefore greater REE adsorption capacity than 1:1 clays (Wang et al., 2017). However, their stronger REE binding capacity hinders leachability resulting in lower desorption efficiencies, as extraction efficiency of REE from clays decreases in the order of kaolinite, illite, muscovite and montmorillonite (Brigatti et al., 2013; Schoonheydt et al., 2018). Fluid pH also controls absorbability, as slightly acidic to near-neutral conditions are suggested to be optimal for REE adsorption, while low pH pleads to competition from abundant cations for surface sites, and high pH suppresses sorption through REE hydrolysis (Huang et al., 2021; Russo et al., 2025). Under near neutral to alkaline conditions, REE also form highly stable aqueous complexes which preferentially retain HREE, thereby limiting their availability for adsorption onto clays. In such circumstances, LREE are adsorbed onto clays under higher pH conditions (Johannesson et al., 2000).

Apart from clays, Fe-Mn (oxy) hydroxides such as goethite, hydrous ferric oxide, birnessite and pyrolusite also adsorb/scavenge REE through surface complexation, such as in the supergene Mn formations from the greenstone belt of Dharwar Craton (Fig. 4; Harshitha et al., 2024). As these minerals have high surface areas and variable-charge surfaces which facilitate strong inner-sphere complexation with REE^{+3}, resulting in preferential uptake of MREE and HREE by Fe oxyhydroxides, and pronounced Ce enrichment in Mn oxides due to their ability Ce^{+3} oxidation to insoluble Ce^{+4} (Ohta and Kawabe, 2000, 2001; Davranche et al., 2005). Similar to clays, the adsorption depends on the pH, where uptake generally increases with rising pH because deprotonation of surface hydroxyl groups enhances their binding capacity (Davranche et al., 2004, 2005). The extent of REE adsorption is also influenced by the abundance and competition from inorganic and organic ligands present in the solution which form strong REE complexes that reduce their availability for surface binding, while humic complexes can physically shield REE from oxide surfaces and suppress Ce anomalies. During burial or diagenesis, these Fe-Mn oxyhydroxides may dissolve, transform or remobilize the adsorbed REE into secondary minerals, making them highly effective, but often intermittent sinks that affect the REE patterns in weathered profiles, marine as well as supergene sediments.

3.2.3. Organic-rich sediment accumulation

In black shales, deep sea mud, peat, coal deposits and phosphorites, organic matter is an important secondary sink for REE, as humic and fulvic substances including carboxyl, phenolic and phosphate groups form stable inner- and outer sphere complexes with REE, with binding strength typically increasing from LREE to HREE due to progressive lanthanide contraction. This mechanism is well illustrated by the REY-rich (Rare-Earth Elements and Yittrium) deep sea-mud around the Minamitorishima island of Japan with more than 0.5% ppm REY, mainly hosted within biogenic calcium phosphates (Takaya et al., 2018). In shallow marine environments, organic matter exerts a strong control on phosphate diagenesis, as the degradation of organic debris enhances porewater phosphate concentrations, thereby influencing the precipitation and recrystallization of carbonate-fluorapatite, into which REE are readily substituted, as observed in early Cambrian phosphorites of South China (Mei et al., 2025). Similarly, organic-rich black shales act as REE sinks, due to strong complexation with organic matter and subsequent incorporation into authigenic phosphate and Fe-Mn oxide phases, as demonstrated in REE-enriched shale units of the Baiguoyuan deposit, China

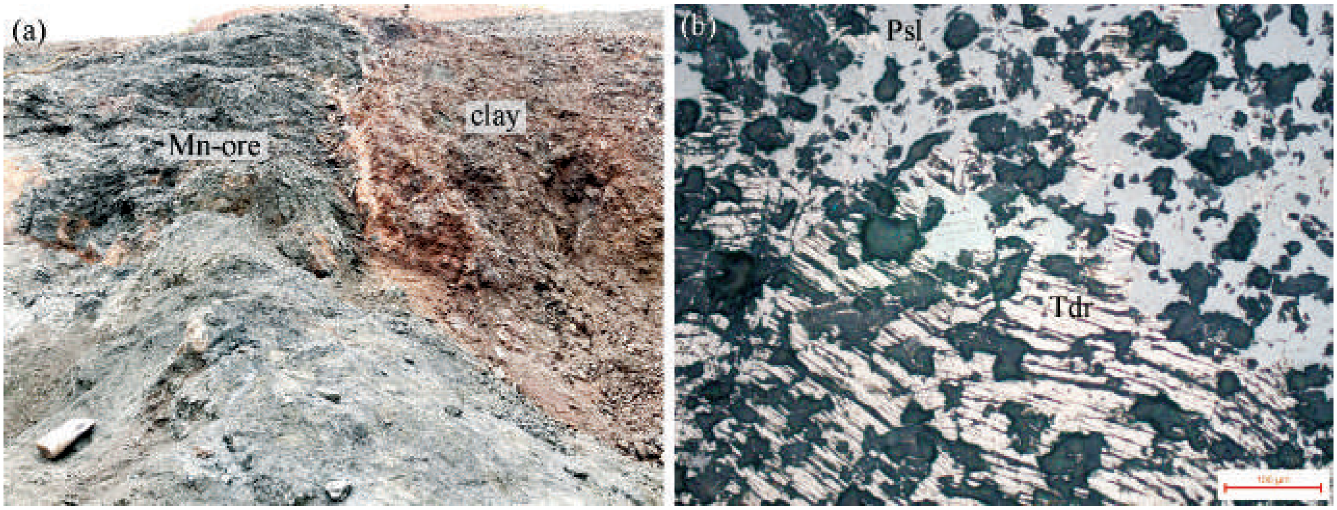

Fig. 4: (a) Field photograph of pocket-type Mn ore enclosed within clays in Sandur greenstone belt, Dharwar Craton, (b) reflected-light photomicrograph illustrating fibrous todorokite (Tdr) intergrown with psilomelane (Psl), wherein todorokite is identified as the main REE-hosting mineral.

(Yang et al., 2011). Among these deposits, organic matter acts both as a carrier and a trap where dissolved organic ligands facilitate REE transport as colloidal complexes, while flocculation, redox changes, and early diagenesis immobilize REE into organic matrices, diagenetic phosphate and refractory kerogen-bound phases.

3.2.4. Sedimentation rate

In REE deposits formed through coastal, fluvial or eolian depositional processes, sedimentation rate plays a key role in the concentration, preservation and spatial distribution of REE-hosting heavy minerals (HM) within both beach and inland environments. In high sedimentation rate sediment accumulation such as delta fronts, prograding shorelines and aggrading fluvial systems, rapid deposition leads to the burial of HM-rich sands before extensive hydrodynamic sorting takes place (Morin-Ka et al., 2025). However, the selective removal of lighter minerals by wave action, longshore drift or aeolian processes prevents the concentration of HMs. Furthermore, faster sedimentation rates rapidly trap REE-bearing particles minimizing remobilization and facilitating their burial, thus protecting from erosion. Hence, rapid sedimentation systems tend to preserve lower grade and less mature HM assemblages, unless there is post-depositional reworking (Amalan et al., 2018). In contrast, prolonged periods of low sedimentation are conducive to the gradual removal of lighter minerals resulting in well sorted high-grade REE-HM deposits, which generally form along stable passive margins and in coastal embayments where longshore transport decreases (Dushyantha et al., 2020). In low sedimentation conditions, i.e. arid climates, tectonically quiescent basins or in regions of marine transgressions, waves and currents repeatedly rework the same basin-fill deposit causing an overall increase in mineralogical maturity that favors the accumulation of REE-bearing minerals such as monazite, xenotime, zircon and allanite (Hou et al., 2017). Although decreased sedimentation rates increase the exposure to reworking, they also allow prolonged interaction with porewaters, leaving HM susceptible to wind deflation, abrasion or removal during storm events.

In deposits formed through diagenesis or seawater precipitation such as sedimentary phosphorites, reworking enhances the grade as repeated agitation and winnowing tend to concentrate REE-rich phosphate phases (Soudry et al., 2013). In most Phanerozoic continental shelves, pristine phosphorites formed during transgression are often reworked into high-grade regressive lags with 25-35% P_2O_5, and therefore abundant apatite and accessory phosphate minerals hosting REE (Zhang et al., 2021; Wigley and Compton, 2007).

4. Conclusions

In view of the limited availability of primary REE resources in the country and the issues related to complex extraction methodology and environmental challenges for their exploitation, it is necessary to pay attention on secondary resources to meet our REE demand to some extent. The utilization of secondary deposits may avoid our dependency on other countries. By using the industrial and mining waste will naturalize the waste products near the mining and industrial sites thereby providing a safe environment to society. Further, it is faster compared to that of primary deposit mining. Knowledge about the processes involved in REE mobilization, transport and deposition may guide more efficient identification of new secondary REE deposits in future.

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SIGNIFICANT ROLE OF SACRED SPACES FOR CONSERVATION OF GEODIVERSITY-INTERCONNECTEDNESS AND SUSTAINABLE FUTURES

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ABSTRACT

Sacred spaces or groves are traditionally the areas of religious and cultural significance. They are often associated with unique geological features or landforms. However, there is general paucity of research that acknowledges the interconnectedness of geodiversity - natural and cultural heritage. Relationships between geoheritage and cultural heritage are being increasingly explored and have become one of the mainstreams within studies of geoheritage geodiversity and geoconservation. Geodiversity is a non-renewable resource and hence urgent need for adapting effective strategies for its conservation or making use of existing community practices for protection of sacred spaces and promoting pristine aspects of nature. It is evident that geoscientific attention is warranted for documentation of interconnectedness of sacred spaces and sustainable futures of conserved natural heritage sites with dedicated participation of local community. Significant role being played by the community supported sacred spaces for conservation of biodiversity together with geodiversity and their interconnectedness for overall sustainable futures are discussed with selected global and Indian case studies.

Key words: *Sacred groves, Geological monuments, Geodiversity, Conservation*

Introduction

Sacred groves or sacred natural sites (SNS) are community-regulated and conserved patches of forest land. They have cultural and ecological significance to the local community. Sacred Grove represents the major effort to recognize and conserve biodiversity (ethnic diversity) traditionally. The age-old system of every village having a temple, a tank and associated sacred grove explains the ancient method of water harvesting and sharing and may be considered as the backbone of village economy. The existence of sacred groves in India dates back to ancient pre-agrarian hunter gathering era and their presence has been documented since early 1800's. Harbouring firm beliefs that the trees are the abode of deities and ancestral spirits, many communities set aside sanctified areas of forest and established rules and customs to ensure their protection prohibiting felling trees, killing animals etc. The prevailing belief among devotees is that the presiding deities administer punishment to individuals or entire community in the form of diseases or crop failure if they violate the established customs. As a result of such restrictions and strict adherence to the accepted customs by the devotees, several endemic and endangered plant and animal species have survived in the sacred groves for so many years since. Such collective community support and immense faith promote the sustenance of sacred groves that have attained religious and holy significance (Malhotra, et al. 2001)

Sacred groves have existed in India from time immemorial as patches of densely wooded areas, venerated on religious grounds. Sacred groves have preserved many rare and endemic wild plant species, many of which hold potential benefit to man in medicine, agriculture and industry. In fact, sacred groves represent the ancient Indian way of in situ conservation of genetic

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diversity. Reverence for all forms of life human, animal or plant, characterizes our ancient tradition and continues to this day as a legacy laced with spirituality, humility and recognition of the importance of the elements and nature. Sanctity attached to places where nature shows her bounty was both spiritual and secular. These places were considered 'sacred', as Gods were supposed to bless them and naturally their protection was considered an obligation on the part of the society. Thus, many a sacred grove has been preserved as sustainable resources, ensuring the basic capital intact. These sacred groves are therefore valuable gene pools and the first major effort to recognize and conserve biodiversity and impacts of global and national policy on the management and conservation of sacred groves of India (Ormsby, 2011).

Geodiversity refers to the variety of the geological and physical elements of nature, such as minerals, rocks, soils, fossils, landforms, and active geological and geomorphological processes. Geodiversity also acts as a natural laboratory and textbook, teaching new generations about Earth's history, sustainable use of the Earth's resources and the science necessary to overcome the challenges of tomorrow. Scientific knowledge about how geological and geomorphological processes occur in nature is extremely important for risk/disaster prevention (earthquakes and tsunamis, volcanoes, floods, landslides, etc.) and to support smart solutions on land use planning and spatial management. Science based on geodiversity contributes to understanding past changes to the climate. This knowledge can then be applied to understanding how climate may change in the future, allowing a more effective adaptation. Therefore, geodiversity is the foundation of communities, and an intrinsic part of humanity's relationship with nature. Geodiversity is also the basis for the landscapes that underpin geotourism, such as mountains, caves and coasts. This produces and has the potential to produce significant economic benefits for local populations. Landscapes provide an identity for local and indigenous communities and attract individuals to explore the world in their leisure time (Wadhawan, 2020a & b; 2021).

Geodiversity has varied value components that reflect the physical basis upon which ecosystems and anthropic activity settle. The geodiversity entails seven values (Gordon, 2018; Reynard and Giusti, 2018)**: -** (a) intrinsic, (b) cultural, (c) aesthetic, (d) economic, (e) functional, (f) scientific, and (g) educational. Together with biodiversity, geodiversity constitutes the natural diversity of planet Earth **(**UNESCO, 2015; IUCN WCPA, 2019). Geodiversity term first appeared in Tasmania, Australia (Sharples, 1993; Kiernan, 1996**).** Further, Earth's biodiversity is largely due to diversity of the geological world: the Geodiversity, and that for land management to be fully effective, a holistic understanding and approach is necessary (Gray, 2004**).** Geodiversity is a non-renewable resource and hence urgent need for adapting effective strategies for its conservation or making use of existing community practices for protection of sacred spaces and promoting pristine aspects of nature. The sacred groves and geodiversity sites can be linked because many sacred groves are often found in areas with unique geological features, as sacredness and ecological value are often intertwined with natural landscapes. Present contribution elaborates on the significant role being played by the sacred spaces for conservation of biodiversity together with geodiversity and captures interconnectedness and utilities for overall sustainable futures.

Geodiversity-Religious and Cultural Importance and Interconnectedness

There are several reasons why geodiversity is important. The rocks and geological processes play fundamental regulating service roles. Rocks and sediments play a crucial role in filtering polluted surface water before it reaches groundwater aquifer. Similarly, the natural weathering and alteration of rocks is fundamental for the formation of soils; essential for agricultural uses and the communities that rely on those agricultural products. Human well-being is also based on the diversity of geological resources. They have been used since the early years of human evolution, and play an essential role in the economic and social development of modern society. Wisely used, mineral resources create wealth, employment, a vital social and natural environment, leading to peace. The increase in the number and size of megacities worldwide creates huge challenges.

Sacred groves have been reported from many parts of the world where mostly tribals and indigenous communities live and practise shifting cultivation e.g., Mexico, Ghana, Nigeria, China, Syria, Turkey etc. In India they are known from Himalayas, North-East India, highlands of Bihar, Odisha, Madhya Pradesh, Andhra Pradesh, Karnataka, Tamil Nadu and Kerala. Locally they are known variously as "Sarana" (in central India), "Devrai" and "Deviahate" in Maharashtra, "Devarkadu" in Coorg, 'Orance' in Rajasthan, "Kavu" or 'Nagavanam' in Kerala, "Nandavana" in Tamil Nadu, "Sidharavanam" in Karnataka, "Kavu" in Andhra Pradesh. In some cases, the tallest tree in the grove is worshipped in the belief that it is the incarnation or abode of God. 'Trees such as *Borassus flabellifer; Alstonia scholaris. Antiaris toxicaria, Hopea parviflora, Strychnos nux-vomica, Ficus religiosa* etc. are being worshipped in this way (Balasubramanyan and Induchoodan, 1996; Khumbongmayum, et al. 2004; Murugan, et al. 2008; Kandari, et al. 2014).

Relationships between geoheritage and cultural heritage are multiple: spatial, conceptual, causal, and thematic (Gordon, 2018; Reynard and Giusti, 2018). Besides, part of geoconservation effort is located at the interface with cultural heritage, as the introduction of certain conservation measures may necessitate a good understanding of the local cultural context, including the intangible heritage of indigenous societies and vice versa (Brockx and Semeniuk, 2007; Olson and Dowling, 2018). Sacred spaces, encompassing mountains, forests, caves, and rivers, play a significant role in conserving geodiversity by instilling spiritual and cultural values that protect geological features from human exploitation. Indigenous and local communities develop unique rules, taboos, and traditions based on their reverence for these sites, which promotes environmental stewardship and restricts destructive activities.

Sacred groves and geodiversity sites can be linked because many sacred groves are often found in areas with unique geological features, as sacredness and ecological value are often intertwined with natural landscapes. These areas, including unique rock formations, caves, or specific geological zones, can also hold cultural and religious significance, leading to their protection as sacred groves**.** The preservation of sacred groves by local communities serves as a form of community-led conservation, which can indirectly protect the associated geological features from industrialization or exploitation. Sacredness often arises from the unique nature of a place, which can include its geological aspects such as distinctive rock formation, a cave, a spring, or an area with unique soil type that might be seen as a dwelling place for spirits or deities, thereby becoming a sacred grove.

Sacred spaces and conservation of geodiversity

The geology of a region, including soil types and landforms, is the foundation upon which biodiversity thrives, and conserving it, preserves the entire ecosystem. Geodiversity underpinning biodiversity has been globally well established. By protecting the geological foundations within a sacred space, these cultural practices also protect the biodiversity it supports. Numerous global examples demonstrate the role of community supported sacred sites in sustainable geoconservation practices. Some selected examples of sacred sites preserving geodiversity (UNESCO, 2015; IUCN WCPA, 2019) include the following:

- **Uluru, Australia:** This monolith is a sacred site for the Anangu, the Aboriginal people of the area. Their spiritual and cultural connection to Uluru and its geological formations ensures its protection and limits human impact.
- **Petra, Jordan:** The archaeological site of Petra in Jordan, with numerous elaborate structures

dated to the turn of BC/AD times, half-built and half-carved into striking red sandstone outcrops. Geomorphology provides a magnificent setting to the ancient city, with high cliffs, rock platforms, extremely narrow gorges, and a variety of selective weathering features.

- **Tibetan Mountains:** Sacred mountains in Tibet and other parts of Asia are often regarded as the homes of deities, with traditional rituals and taboos protecting the landscape from exploitation. This practice helps maintain the "topocosmic equilibrium" and prevents degradation of these unique mountain landscapes, including the sacred Kailash Mountain region.
- **Meteoran Monasteries, Greece:** The monasteries at Meteora are built atop impressive conglomerate rock towers. The spiritual significance of the site has protected both the human-made structures and the spectacular geological formations of the landscape.
- **Hariyali Devi Landscape, India:** In Uttarakhand, the Hariyali Devi sacred landscape is revered by local communities. The associated beliefs, rituals, and socio-cultural practices contribute significantly to conserving its biodiversity and preserving the unique geomorphology of the Garhwal Himalaya.

Although there are several global examples that demonstrate the role of sacred cultural sites in geoconservation of geodiversity, only three of such illustrative examples of interconnected geodiversity and biodiversity valued and conserved by local community as the sacred reserves and spaces are briefly elucidated in the following sections.

1. Uluru (Ayers Rock-Mount Olga) National Park, Australia

Cultural and spiritual beliefs attached to geological sites often establish them as areas of profound respect and protection. Awe and reverence to such natural sites promote beliefs amongst many cultures who associate geological formations like mountains, volcanoes, and unique rock formations with powerful deities, spirits, or ancestors. The resulting fear and reverence can lead to the establishment of strong community beliefs and rules against exploitation, vandalism, or trespassing. Uluru-Kata Tjuta National Park - UNESCO World Heritage Centre comprises a massive monolith that is a sacred site for the Anangu, the Aboriginal people of the area near the centre of Australia in the southern part of the Northern Territory, 335 km (208 mi) south-west of Alice Springs (Fig. 1). Their spiritual and cultural connection to Uluru and its geological formations ensures its protection and limits human impact. This Inselberg is a monolith of arkose-sandstone formation that stands 348 m (1,142 ft) high, rising 863 m (2,831 ft) above sea level. The site has a deep cultural and spiritual significance to the aboriginal Anangu people who have traditionally owned the Cultural Centre within the National Park (UNESCO, 2015).

Fig. 1: Uluru (Ayers Rock - Mount Olga) National Park, Australia. The protected site has a deep cultural and spiritual significance to the aboriginal Anangu people.

The other suitable example of sacred spaces and conservation of geodiversity in Indian context is considered from the Tirupati-Tirumala region in Andhra Pradesh.

The sacred and protected spaces around Sri Venkateshwara Swami [Sri Balaji] Temple have helped in conservation of two important officially recognized geoheritage sites by GSI-the National Geological Monuments (NGMs): the Eparchean Unconformity and Natural Arch (GSI 2001; Wadhawan, 2016; 2020a; 2021). Such interconnectedness of Cultural and Geoheritage is further elaborated in the following paras that record the occurrence and preservation of two major notified National Geological Monuments (NGM) as follows.

2) The Natural Arch NGM:

It is one of the most popular natural tourist sites in Andhra Pradesh.

3) The Eparchean Unconformity:

This is the boundary between the sedimentary rocks of the Cuddapah Supergroup (1,600 Ma), and the underlying Archaean rocks comprising granites, gneisses and intrusive dolerite dykes and sills that are more than 2,100 Ma around the sacred Tirumala Hills in Andhra Pradesh.

NATURAL ARCH

Protection through cultural and spiritual values provide credence to the myths and legends that are often woven around sacred geological sites, embedding their importance into the collective memory of a community. The NGM of the Natural Arch, is one of the most popular natural tourist sites in Andhra Pradesh. Legend has it that Lord Venkateshwara Swamy made his appearance through this natural arch as a SWAYAMBHU and later occupied his present seat at the sacred Tirumala Temple. It is locally called *Silathoranam*, literally meaning ‘a garland of rocks’ (Fig. 2). Crescent shaped Cuddapah Basin of Peninsular India is developed over Eastern Dharwar Craton of Archaean - Peninsular Gneissic Complex [Granitic and Gneissic terrain] with intrusive dolerite dikes and sills. It is a naturally formed arch at the Tirumala Hills in Andhra Pradesh. This natural structure is the result of natural weathering and formed in the interbedded quartzites and shales of Cuddapah Supergroup of Middle to Upper Proterozoic age (1,600 to 570 Ma) due to natural erosive forces operative for the last several million-years.

EPARCHEAN UNCONFORMITY

Eparchaean Unconformity, a notified National Geo-heritage Monument, is a major discontinuity of stratigraphic significance that symbolises an era of prolonged break in the earth’s history. This national geological monument is located in the Tirupati valley, between 13.50°N 79.37°E/ 13.50°N 79.37°E and 13.45°N 79.75°E/ 13.45°N 79.75°E with an insight into the formation of this part of the subcontinent, the intricate orogeny, the exciting paleoenvironment and the incidence of fascinating paleo-flora and fauna.

Eparchean Unconformity represents the boundary between sedimentary rocks – the Proterozoic Nagari

Fig. 2: The Natural Arch NGM, is one of the most popular natural tourist sites at the Tirumala Hills in Andhra Pradesh, India

Quartzites of the Cuddapah Supergroup, 1,600 million years in age, and underlying Archaean granite comprising variously weathered granites, gneisses and intrusive dolerite dykes and sills that are more than 2,100 million years old. The line that separates these two - The Eparchaean Unconformity - is not a fracture, or a fault, but a stupendous pause in the creation of the earth's crust. This temporal hiatus spanning nearly 500 million years is enormous time lag in the creation of the earth's crust. It is also supposed to be a remarkable period of geological stability, quiescence without structural disturbance and related igneous activity. The geological history of the earth evidenced in abrupt changes and discontinuity in the rock's form and structure in the earth's crust. can be seen in the steep natural slopes, road scars and evolving ravines in the Tirupati-Tirumala Ghat road in Chittoor district of Andhra Pradesh. The geographic extent of the basin is outlined by the hill ranges of Palakonda-Vellikonda on one side and Sanumbatla-Srikalahasti alongwith Nagari ranges of the Eastern Ghats mobile belt on the other. Tirupati temple is the most auspicious of all pilgrimage centres in South India is located in the midst of the range of hills. The hills enclose the temple town giving it the shape of an amphitheatre.

As the entire Tirumala Hill and the landscape hosting the sacred Balaji Temple is protected and conserved, similarly the NGM of Eparchean Unconformity also gets protected from the modern developmental schemes like infrastructure construction, mining, and deforestation. This preserves the integrity of the geological landscape and the geodiversity it contains, including specific rock outcrops, soil profiles, and associated hydrological features (Fig. 3). Community-enforced taboos can ban resource extraction from such areas, such as forbidding the collection of timber, extraction of stones, or hunting, which all help preserve the geodiversity and biodiversity for sustainable future.

Fig. 3: Eparchean Unconformity represents the boundary between sedimentary rocks – the Nagari Quartzite of the Cuddapah Supergroup, 1,600 million years in age, and underlying Archaean rocks of more than 2,100 million years old.

DISCUSSION AND THOUGHTS ON WAYS FORWARD

Although the cultural values associated with sacred spaces and forested groves are considered as superior, this should not lead to the neglect of geodiversity and geoheritage aspects at these sites. There are several sacred spaces and groves in India that host rare and unique geodiversity and geoheritage sites. Sensitivity and vulnerability of geosites vary and need to be assessed for conservation. There are potential threats to conservation of sacred groves hosting the geodiversity sites that include: 1) natural processes such as weathering and erosion, and 2) human activities such as the settlements, and infrastructural development, mining and pollution etc.

Protection of the environment and life supporting systems are interwoven with conservation of biological and geological diversity. Sacred groves represent this all-embracing concept and practice of ancient Indian way of in situ conservation of genetic diversity related to the landuse aspects. Besides, sacred groves, in general act as a nursery and store house of many of the local ayurvedic, tribal and folk herbal medicines. Fruits of *Artocarpus, Syzygium, Salacia, Phyllanthus, Mangifera, Buchanania, Carissa, Garcinia* etc. are eaten by birds and animals (mostly nocturnal) in the sacred groves. Further, as an ecosystem, the environmental significance of the sacred groves is highly valued. In fact, they even help in soil and water conservation besides preserving its rich biological wealth. The ponds and streams adjoining the groves are perennial water sources. These are the last resorts to many of the animals and birds for their water requirements, especially during summer. Sacred groves also enrich the soil through its rich litter composition. The nutrients generated thus are not only recycled within the sacred grove ecosystem but also find their way into the adjoining agro-eco systems.

Traditional governance by indigenous communities has preserved sacred sites for centuries, sometimes more effectively than modern legal frameworks. Recognizing and integrating this spiritual governance into modern conservation strategies can improve the effectiveness of geoconservation efforts. In spite of the very high land to man ratio, these groves have been thriving, which naturally shows the very high reverence and importance some people attach to these sacred groves. At a time when evergreen forests have been dwindling at an alarming rate in the Western Ghats, preservation and management of these sacred groves are unavoidable, for each of this is a treasure house of rare species, germplasm collection of all the plants in an area, and abode of rare, medicinal and economically important plants (Pushpangadan, et al. 1998). An added advantage is explored for conservation of geodiversity and unique geoheritage sites contained within the sacred spaces that have been traditionally protected and worshiped by local community.

Conservation of geodiversity and geoheritage sites within the sacred spaces can be affected through: -

1. Creating Protected Area with supporting Legal Regulations and framework
2. Fencing or placing such sites within the specially constructed buildings/shelters, e.g., the Fossil Wood sites etc.
3. Community Driven Conservations such as the protection of Sacred Spaces leading to holistic & integrated geoconservation of Geodiversity and Biodiversity
4. Sacred spaces protected by the local community are obviously the low hanging fruits that conserve geodiversity around world heritage sites in India - vigorous publicity & awareness campaigns need to be mounted for sustainable conservation and socio-economic futures.
5. Government may encourage the owners who are willing to conserve their private sacred groves by giving them incentives in the form of maintenance grants or awards.

6. Create awareness in the public about the importance of these groves and the necessity for their preservation through mass media like All India Radio and Door Darshan and social media campaigns.

7. Encourage private ownership, e.g., a Trust – such as the Mehrangarh Fort & Museum Trust, Jodhpur, Rajasthan and the Tirumala - Tirupati Devasthanam (TTD) which have been very successful in conservation of the designated geoheritage sites along with the cultural and spiritual heritage associated with the landscape.

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GEOLOGICAL IMPACTS OF URBANIZATION IN INDIA: AN EMERGING FRONTIER

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ABSTRACT

Rapid and unplanned urbanisation in India is driving significant transformations in near-surface geological systems through intensive surface loading, altered hydrology, and groundwater extraction. This study synthesises geodetic, hydrogeological and geomorphological evidence to demonstrate how major Indian cities are emerging as active geological systems. InSAR analyses reveal substantial subsidence in Delhi, Ahmedabad and Kolkata, while Himalayan towns such as Joshimath exhibit slope instability linked to excavation, drainage modification and weak lithology. An empirical case study from the Bhubaneswar–Cuttack metropolitan corridor further illustrates the coupling between urban expansion and geological response. Between 1990 and 2020, Cuttack's maximum land surface temperature rose from 32.07°C to 38.67°C, driven by a 58.19% increase in built-up area and a 51.39% decline in vegetation. Twenty-seven municipal wards are now classified as highly heat-vulnerable and environmentally unsuitable. Groundwater levels in Bhubaneswar have declined by 0.3-0.8 m/year, contributing to aquifer compaction and local subsidence (8-15 mm/year), while microzonation studies classify large areas as Site Classes C & D, indicating susceptibility to consolidation and seismic amplification. These findings establish that urbanisation is not merely a land-use transition but a geological process reshaping stress fields, sediment behaviour and long-term landscape stability. Integrating geological insights into planning is essential for sustainable urban development.

Keywords: *Urbanisation; Land subsidence; Groundwater depletion; InSAR; Urban geology*

Introduction

India is undergoing one of the most rapid and spatially extensive urban transitions on Earth. Current demographic projections by the United Nations and India's Census Bureau suggest that the nation's urban population about 377 million in 2011 is expected to exceed 600 million by 2036, accounting for nearly half of all Indians. This transformation, occurring within a few decades, is altering the natural and geological landscape at an unprecedented pace and scale. Unlike the relatively gradual urban growth experienced in industrialised nations, India's expansion is highly uneven and geographically diverse encompassing the alluvial plains of the Ganga and Yamuna, the basaltic plateaus of the Deccan, the coastal deltas of the Bay of Bengal and Rann of the Arabian Sea, and the steep Himalayan and Western Ghats hill slopes. Each of these physiographic regions possesses distinct geological characteristics, hydrological systems, and structural sensitivities, and thus responds differently to the pressures imposed by urbanisation.

The rapid spread of built-up areas introduces a variety of geological stresses. The proliferation of high-rise buildings, bridges, metros, and highways imposes significant surface loading, altering the natural stress distribution in the shallow crust. The replacement of natural soil and vegetation with impervious materials such as asphalt and concrete drastically reduces infiltration, modifying both surface runoff and groundwater recharge. Simultaneously, cities depend

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heavily on groundwater extraction to meet domestic, industrial, and construction needs. The cumulative effect of over-extraction, reduced recharge, and heavy structural loading leads to subsurface deformation manifested as aquifer compaction, land subsidence, and ground fissuring. These changes are no longer hypothetical; satellite-based interferometric synthetic aperture radar (InSAR) monitoring has confirmed measurable subsidence in megacities like Delhi, Ahmedabad, and Kolkata, where the ground is sinking by several millimetres to centimetres per year (Garg et al., 2022; Gogoi et al., 2025).

Besides the subsurface, urbanisation transforms geomorphological and sedimentary processes. Channelisation of rivers, reclamation of wetlands, and modification of drainage networks alter sediment transport, increasing flood frequency and erosion in peri-urban areas. In coastal cities such as Mumbai and Chennai, land reclamation and unregulated construction on deltaic sediments compound natural compaction and sea-level rise, heightening vulnerability to inundation. In Himalayan hill towns such as Joshimath, Nainital, and Shimla, the excavation of slopes, obstruction of natural drainage, and unplanned construction on weak colluvial deposits have triggered slope instability and ground movement, exposing the intimate coupling between urban expansion and geological fragility (Tiwari et al., 2023).

These processes have far-reaching implications for infrastructure integrity, groundwater sustainability, disaster resilience, and the long-term evolution of India's landscapes. Yet, geology remains marginal in most urban planning frameworks. Urban master plans and engineering guidelines tend to treat the ground as static foundation material, rather than a dynamic, interacting system. Consequently, geologically induced hazards subsidence, slope failure, or aquifer depletion are often recognised only after damage occurs. Addressing this gap requires reframing the relationship between cities and the solid Earth. The emerging field of *Urban Geology* seeks to do this precisely: integrating geological, geotechnical, hydrological, and remote-sensing insights to understand how urbanisation interacts with the lithosphere. This article synthesises mechanistic understanding, empirical evidence, and policy implications to highlight the geological footprint of India's urbanisation, and to propose a framework for sustainable growth grounded in the realities of the Earth beneath our cities.

Urbanisation and the Geological System: A Conceptual Overview

Urbanisation interacts with the geological system through a network of physical, hydrological, and chemical processes that operate across scales from the grain structure of sediments to the regional crustal stress field. The built environment does not simply rest upon the geological substrate; rather, it becomes integrated with it, imposing new stresses, redistributing fluids, and altering the long-term stability and evolution of near-surface materials. These interactions are cumulative and often nonlinear, creating feedbacks that intensify over time as cities expand both vertically and horizontally.

At the most fundamental level, surface loading from buildings, highways, and engineered fill adds substantial vertical stress to the ground. In unconsolidated or weakly lithified sediments, particularly clays and silts, this load enhances consolidation and pore collapse, causing settlement. While a single building may affect only a few metres beneath its footprint, the aggregate load of an entire urban landscape, mega-tonnes of concrete and steel can modify stress regimes regionally, leading to measurable ground deformation. This process is accentuated in lowland plains such as Delhi, Lucknow and Kolkata, where thick Quaternary alluvium hosts compressible aquifers and aquitards. Over time, such consolidation not only reduces porosity but also changes permeability, which affects subsurface fluid circulation (Pandit et al., 2025).

Simultaneously, impervious cover alters the hydrological balance. The replacement of soil and vegetation with concrete and asphalt drastically reduces infiltration capacity sometimes by more than 80%. Rainwater that once recharged aquifers now becomes surface runoff, entering storm drains and rivers. The reduction in recharge diminishes groundwater replenishment, while the concentration of runoff accelerates erosion along channels and urban peripheries. In many Indian cities, seasonal flooding is partly attributable to this hydrological reconfiguration, where natural infiltration zones have been sealed or built over.

A third, closely linked process is groundwater withdrawal, which lowers pore-water pressures, increases effective stress, and induces compaction within aquifer systems. In fine-grained interbeds, such as clays within alluvial aquifers, this compaction is largely irreversible, resulting in permanent loss of aquifer storage and surface subsidence. As observed in Delhi, Ahmedabad and Kolkata, the sinking ground is not simply a surface phenomenon but reflects deep-seated adjustments to altered stress and fluid regimes. The hydromechanical coupling between withdrawal and compaction exemplifies the tight integration of urban water management and geological response.

Further, excavation and slope modification for urban infrastructure; road cutting, tunnelling, quarrying and terracing perturb natural equilibrium slopes. Removal of toe support, interception of drainage lines and loss of vegetation reduce shear strength and increase susceptibility to landslides or creep. The effects are especially acute in hilly terrains such as the Himalayas and Western Ghats, where anthropogenic modifications coincide with heavy monsoon rainfall and seismically active bedrock.

Equally significant is the impact of urban infrastructures on sediment and fluvial systems. Dams, embankments, and land reclamation trap or divert sediment, altering downstream geomorphology. Rivers passing through cities often show channel narrowing, incision, or aggradation, depending on the balance between trapped sediment upstream and enhanced erosion from impervious runoff. These geomorphic adjustments can, in turn, influence local base levels and groundwater gradients (Naik et al., 2008).

Lastly, chemical and geochemical changes accompany urban development. Pervasive contamination from industrial effluents, vehicular emissions and construction waste introduces heavy metals, salts and hydrocarbons into soils and aquifers. These inputs modify mineral weathering reactions, alter pH and redox conditions and can lead to secondary mineral precipitation or dissolution, thereby changing geotechnical behaviour (Shimod et al., 2022).

These mechanisms are interdependent and mutually reinforcing. Compaction decreases permeability, which further limits recharge; reduced recharge deepens dependency on pumping, amplifying subsidence. Increased runoff mobilises fine sediments that clog drains and rivers, altering hydrology and flood patterns. In hilly areas, slope instability contributes debris that modifies valley morphology and sediment flux. Through these feedback loops, cities progressively rework near-surface geology on human timescales, producing irreversible transformations in the Earth's shallow crust. Urbanisation, therefore, should not be viewed merely as an environmental or socio-economic process, but as a powerful geological force actively reshaping the lithosphere beneath modern civilisation.

Land Subsidence: The Most Visible Geological Consequence

Land subsidence of ground surface elevation has emerged as a conspicuous geological signature of urbanisation. Mechanistically, sustained groundwater pumping reduces pore pressure and places additional effective stress on aquifer skeletons; in fine-grained, compressible strata this yields consolidation and irreversible volume loss. Satellite techniques, notably Interferometric Synthetic Aperture Radar (InSAR), have enabled widespread detection and mapping of subsidence with millimetre precision. In India, InSAR studies have revealed subsidence hotspots associated with intense extraction and compressible sediments. For example, Sentinel-1 PS-InSAR analysis over Delhi–NCR documented subsidence rates across portions of the alluvial plain during 2014-2020, with affected zones closely correlated with long-term water table declines (Garg et al., 2022). Similarly, regional reviews and more recent InSAR syntheses highlight subsidence in deltaic and urban basins such as Kolkata (Gogoi et al., 2025) and report alarming locally high rates in parts of Ahmedabad where Sentinel-1 SBAS analysis identified maximum sinking up to ~35 mm per year in Bopal and Vatva between 2020 and 2023 (Pandit et al., 2025; Dolma et al., 2025). The Himalayan town of Joshimath provides a stark example where urban expansion, slope instability and seepage have combined to produce rapid ground deformation, building damage and evacuations (Naik et al., 2008). Subsidence impacts are multifold: infrastructure distortion (cracked foundations, pipelines, and roads), amplified flood risk in low-lying areas, and reduced aquifer storage. In coastal cities even modest subsidence compounds relative sea-level rise and saline incursion, accelerating loss of usable land. Despite these risks, subsidence monitoring and incorporation of results into municipal planning remain limited in many Indian cities, underscoring an urgent need for systematic geodetic surveillance and water-use regulation (Tiwari et al., 2023).

Groundwater Depletion, Aquifer Compaction, and Sediment Dynamics

Urban growth places heavy demands on groundwater for domestic supply, industry and construction activities. Many Indian cities have transitioned to mixed supply systems where groundwater still provides a substantial fraction of water needs; in some instances, extraction is unsustainable. As groundwater is withdrawn, water tables fall, pore pressures reduce and aquifer skeletons bear more effective stress, producing compaction. This compaction is frequently concentrated in compressible clay or silt layers between coarser aquifers, causing permanent loss in storage capacity and contributing to subsidence at the surface. Empirical studies (Shimod et al., 2022) and remote-sensing observations link water-table decline to deformation (Garg et al., 2022; Pandit et al., 2025). Urban surface sealing compounds the problem: impervious pavements and drainage networks reduce infiltration and natural recharge, diverting water away from aquifers and concentrating recharge in small pervious pockets. In addition, urban works excavation for basements and tunnels, and deposition of construction fill modify subsurface heterogeneity and influence local flow paths. Altered runoff regimes also change sediment transport; urban streams often receive higher loads of fine anthropogenic sediments and construction debris, while channel modifications and embankments trap sediment with downstream consequences. Rivers draining urban catchments such as the Yamuna through Delhi and the Mithi in Mumbai show clear morphological adjustments and reduced conveyance, which over time change floodplain stratigraphy and may interact with subsidence patterns. Thus, groundwater dynamics, aquifer mechanical response and surface sediment regimes are tightly coupled in urban settings.

Slope Instability and Terrain Modification

Urban expansion into hills and foothills common in Indian hill stations and rapidly urbanising mountain towns dramatically elevates slope failure risk. Terracing, road cuts, building pads, and other excavations remove toe support and vegetative reinforcement, while storm water and poorly engineered drains increase infiltration and pore pressure. Himalayan and Western Ghats towns are especially vulnerable due to steep gradients, weakly consolidated sediments, intense monsoon precipitation and active tectonics. Multiple studies and disaster reports point to rising incidence of urban and peri-urban landslides: localized slope failures and debris flows following construction activity and extreme rainfall are now documented in Dehradun valley, Shimla and parts of Uttarakhand, culminating in acute crises such as Joshimath where building cracks and localized subsidence forced evacuations (Naik et al., 2008, Tiwari et al., 2023). The geo-mechanical processes include loss of matric suction in unsaturated slopes, progressive failure via tension cracking and basal shear, and mobilisation of colluvium, where anthropogenic fill overloads weak substrates. Beyond immediate hazards to life and property, slope failures remobilise large volumes of sediment into streams, changing channel form and potentially contributing to downstream aggradation and flood hazard. Mitigation requires rigorous slope-stability zoning informed by geological mapping, restrictions on hill cutting, engineered drainage and retaining structures, and reforestation measures to restore root reinforcement and evapotranspiration balance.

Stress Redistribution and Induced Seismicity

Large-scale anthropogenic activities alter stress fields in the upper crust. Two principal pathways operate in urban contexts: surface loading from dense infrastructure and mass movement, and pore-pressure changes from groundwater extraction or fluid injection. Although the magnitude of anthropogenic stress perturbation is small compared to tectonic stresses, faults may be critically stressed and thus sensitive to minor changes. International experience from reservoir impoundment, hydrocarbon extraction and wastewater injection underscores the potential for induced seismicity in susceptible settings. In India, modelling studies suggest that cumulative urban loads and groundwater fluctuations can adjust stress by several kilopascals on shallow basement structures (Times of India, 2025) a scale which could, under specific conditions, alter frictional stability on nearby faults. Empirical evidence directly linking urbanisation alone to seismicity in India remains limited; however, the combination of urban load, extraction-driven pore-pressure changes and proximity to active fault systems provides a plausible mechanism for micro-seismic modulation. Systematic micro-seismic monitoring, integrated with InSAR deformation records and groundwater observations, could reveal subtle anthropogenic contributions to seismic patterns and should form part of an "urban geoseismology" initiative aimed at detecting and interpreting small events and stress changes in and around major urban centres.

Chemical and Pedological Alteration

Urban activities create distinctive changes in soil composition, structure and chemistry that have geological significance beyond immediate environmental and health concerns. Construction, demolition, landfill and industrial emissions transform natural soil horizons into heterogeneous technogenic deposits, often laden with construction rubble, ash, slags, plastics and metal fragments. Atmospheric deposition of heavy metals from traffic and industry accumulates in roadside and urban soils, while leaking sewerage and industrial effluents percolate into shallow aquifers. Studies across Indian towns' document elevated concentrations of Pb, Zn, Cd and other pollutants in urban soils altered pH regimes and increased salinity in coastal wells due to both sea-water intrusion and anthropogenic salt inputs. These chemical changes affect mineral weathering pathways, clay swelling/shrinkage behaviour and aggregate stability, thereby modifying geotechnical properties such as cohesion and permeability (Associated Press, 2023). Over centennial to millennial timescales, urban deposits will lithify into a recognisable anthropogenic stratigraphic unit enriched in plastics and industrial by-products constituting a permanent geological signal of urban civilisation. From an engineering viewpoint, foundations and substructures need to account for such chemical alteration, which can accelerate corrosion, reduce bearing capacity or change settlement behaviour.

Coastal and Deltaic Cities: Combined Natural and Anthropogenic Subsidence

India's coastal and deltaic urban centres occupy deposits that are often naturally compressible and prone to subsidence. Compaction of Holocene deltaic sediments, tectonic subsidence in some basins and eustatic sea-level rise form the background against which urban impacts are superimposed. Anthropogenic drivers, groundwater extraction, reclamation, and heavy construction accelerate subsidence and heighten flood vulnerability. Kolkata, built on the Bengal basin's soft clays and silts, exhibits long-term settlement by intensive pumping and load addition (Gogoi et al., 2025). Mumbai's reclamation and ongoing loading of former tidal flats has altered local drainage patterns and likely induced differential settlement in certain reclaimed zones. In Chennai and coastal Gujarat, saline intrusion into coastal aquifers due to over-pumping has deteriorated groundwater quality and reduced usable freshwater resources, while compaction amplifies sea-level impacts. The combined effect is not simply additive; subsidence lowers the relative elevation, increases tidal inundation frequency, and undermines flood defences. Strategic coastal planning must therefore account for both natural subsidence and human-induced deformation, utilising high-precision GNSS, tide gauges and InSAR to track vertical land motion, enforcing groundwater management and limitations on further reclamation.

Empirical Case Study: Geological Impacts of Urbanisation in the Bhubaneswar-Cuttack Metropolitan Region

The Bhubaneswar-Cuttack metropolitan corridor has undergone rapid and largely unplanned urban expansion over the past three decades, resulting in significant geological, hydrological and environmental transformations across this densely populated deltaic region. Situated on the Quaternary alluvium of the Mahanadi delta, the landscape comprises soft sediments, high water tables and a complex network of paleo-channels that make the region inherently sensitive to anthropogenic disturbance (Patra et al., 2021, 2025). Recent satellite-based assessments of urban growth and land surface temperature (LST) patterns in Cuttack provide compelling evidence of the scale and pace of urban-induced alteration. A detailed analysis of spatial and temporal LST trends from 1990 to 2020 shows that maximum LST in Cuttack increased sharply from 32.07°C to 38.67°C, driven principally by a 58.19% increase in built-up area and a 51.39% reduction in vegetation cover (Patra et al., 2022, 2025). These changes have produced an intensified urban heat island effect, with 27 of the city's 59 municipal wards now classified as highly heat-vulnerable and environmentally unsuitable for habitation, while only 13.21% of the urban area remains suitable. The study also highlights that central and western Cuttack particularly Badambadi, Odia Bazar, Mangala Bag and CDA sectors exhibit severe ecological stress due to dense construction, loss of natural drainage and replacement of permeable surfaces with impervious materials. The correlation between built-up area and rising LST, combined with the negative correlation between LST and vegetation or water bodies, establishes urbanisation as the dominant force altering thermal and environmental conditions in the region (Patra et al., 2025).

These environmental changes are closely linked with the region's geological processes, particularly groundwater depletion and associated aquifer compaction. Groundwater monitoring by the Central Ground Water Board indicates long-term pre-monsoon water-table declines of 0.3-0.8 m/year in major neighbourhoods of Bhubaneswar such as Patia, Chandrasekharpur, Kalinga Nagar and Jayadev Vihar, driven by domestic demand, institutional use and reduced recharge due to widespread surface sealing (CGWB, 2023; Panigrahi and Sharma, 2025). In Cuttack, although monsoon recharge temporarily raises water levels, sustained pre-monsoon depletion is observed in densely populated areas like Badambadi and Chauliaganj. Persistent groundwater withdrawal increases effective stress in the underlying alluvial sediments, mirroring patterns documented in other rapidly growing Indian cities where groundwater-induced compaction has been a major driver of land subsidence (Naik et al., 2008). In this study, Sentinel-1 PSInSAR data processed for 2018-2024 reveal localised subsidence ranging from 8 to 15 mm per year across parts of Bhubaneswar, notably in Rasulgarh, Saheed Nagar, Kalinga Nagar and Chandrasekharpur. These deformation zones spatially coincide with areas exhibiting high LST, extensive impervious cover and declining groundwater levels, confirming the close coupling between thermal stress, hydrological imbalance and geomechanical deformation (GSI, 2023).

Complementing these findings, environmental geology and microzonation studies conducted by the Geological Survey of India show that large parts of Bhubaneswar and Cuttack fall under Site Classes C and D, indicating soft, low-velocity sediments highly susceptible to consolidation, amplification and liquefaction. Particularly, the northern and northeastern belts of Bhubaneswar including Chandrasekharpur, Patia and Mancheswar lie on thick alluvial and reclaimed floodplain deposits with shear-wave velocities below 180 m/s, increasing their vulnerability to structural settlement and seismic amplification (GSI, 2023; Das Chatterjee, 2016). The degradation of natural drainage networks further exacerbates geological instability; more than 60% of Bhubaneswar's natural storm-water channels have been encroached upon or modified, elevating flood risk in localities such as Nayapalli and Acharya Vihar (BDA, 2024). In Cuttack, channel constriction and sediment choking along the Mahanadi-Kathajodi distributaries reduce conveyance capacity and intensify waterlogging and urban flooding conditions shown in the LST habitat suitability analysis to coincide with the least habitable and most environmentally stressed wards (Patra et al., 2025).

Finally, the decline in vegetation, increase in built-up area and rising LST have also contributed to geochemical changes within the soil profile. Studies from comparable urban centres in India indicate that loss of vegetative cover and industrial-traffic emissions lead to elevated concentrations of heavy metals such as Pb, Zn, Cu and Cr, altering soil structure, reducing clay cohesion and affecting groundwater quality (CGWB, 2023). Similar trends have begun to emerge within the Bhubaneswar-Cuttack corridor, aligning with the thermal and urbanisation hotspots identified in recent geospatial assessments. Together, the rise in surface temperature, loss of recharge potential, groundwater depletion, deformation of soft sediments and degradation of drainage networks demonstrate that the Bhubaneswar-Cuttack urban corridor is undergoing a clear and measurable shift in its geological behaviour. Urbanisation here is not merely a surface-level land-use change, it is a powerful geological driver modifying the subsurface through hydromechanical, thermal and geochemical pathways, underscoring the urgent need for integrated urban geological planning in this rapidly evolving metropolitan region.

Integrating Geological Perspectives into Urban Planning

Despite mounting evidence for geological impacts, urban planning in India rarely embeds geology as a central pillar. Building codes typically require site-specific geotechnical investigations, but city-scale geological mapping, subsidence risk zoning, aquifer vulnerability assessments and slope-hazard microzonation are not uniformly integrated into master plans. This gap yields unintended consequences: sitting of critical infrastructure on compressible soils without adequate land-failure mitigation, unregulated hill cutting, and the cumulative failure to manage groundwater at aquifer scales. A pragmatic framework for integration would include: (a) urban geological mapping at planning scales (1:5,000 to 1:25,000), combining lithological, geomorphological, hydrogeological and structural layers; (b) mandatory geohazard microzonation for new urban expansions particularly in seismically active, deltaic or hilly regions; (c) open geotechnical databases of borehole logs and monitoring wells accessible to planners and engineers; (d) institutionalisation of urban geology units within municipal bodies or state agencies to ensure geosciences input in permitting; and (e) regulatory instruments tying groundwater extraction permits to aquifer sustainability thresholds. Such integration would enable anticipatory design (avoiding high-risk zones), design of appropriate foundation systems and long-term resilience planning as shown in Figure 1.

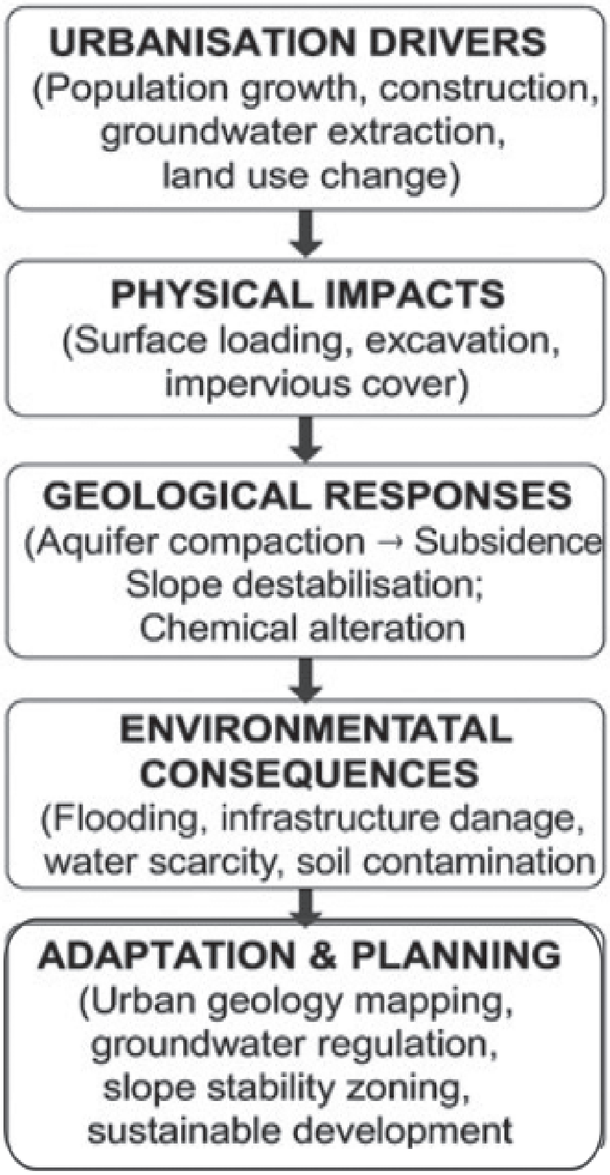

Fig. 1: Simplified schematic diagram showing cause–effect relationships between urbanisation drivers, physical impacts, geological responses, environmental consequences, and adaptation strategies.

Research Priorities and Emerging Directions

To address the knowledge and policy gaps, a concerted research agenda is required. First, a national program of deformation monitoring using InSAR and GNSS should be established for major urban centres to detect subsidence, uplift and differential motion over time. Second, coupled hydromechanical modelling of urban aquifer systems accounting for heterogeneous stratigraphy, engineered loads, and recharge changes will quantify the relative roles of pumping versus loading in observed deformation. Third, targeted field campaigns in hill towns should combine geotechnical boreholes, pore-pressure monitoring, rainfall instrumentation and LiDAR topography to understand slope failure triggers and cutting practices. Fourth, urban soil and sediment geochemistry mapping is needed to quantify contamination patterns and long-term alteration of soil properties affecting engineering performance. Fifth, microseismic networks in select cities should test hypotheses about stress modulation by anthropogenic activity. Sixth, development of urban "digital twins" that integrate geological, hydrological, infrastructural and socio-economic data in real time would provide policy-relevant scenario testing, for example, how groundwater regulation or densification affects subsidence risk. Finally, capacity building is essential; curricula and professional training must embed urban geology into the toolkit of planners, engineers and municipal officers, and institutional linkages between GSI, state groundwater boards, space agencies (for remote sensing), and city corporations should be strengthened.

Urbanisation as a Geological Epoch: The Indian Perspective

Viewed through a geological lens, India's urbanisation constitutes a planet-scale agent of stratigraphic change. Urban processes deposit hundreds to thousands of tonnes of anthropogenic material per hectare concrete, brick, construction debris, plastics and metal creating distinctive surficial horizons that will, in time, be preserved. These anthropogenic layers contain unique chemical signatures (heavy metals, microplastics, synthetic organic compounds) and physical textures (compacted fills, engineered aggregates) that future geologists will recognise as markers of a human-dominated epoch. In India, where urban centres are built across varied lithologies from alluvial plains to basaltic Deccan traps and Himalayan schists the spatial heterogeneity of anthropogenic deposits will be striking.

Moreover, the geotechnical and hydrological legacy of present urban practices, lost aquifer storage due to compaction, modified channel morphologies, and altered slope geometries will persist for centuries to millennia, affecting future landscape evolution. Framing urbanisation as geological process shifts the discourse from short-term planning to stewardship of long-lived Earth system change and underscores the need for precautionary approaches.

Table-1 summarises their geological settings, dominant impacts, observed deformation or geochemical evidence, and key anthropogenic drivers, derived from InSAR studies, field surveys, and published reports.

Table-1: Major Indian cities exhibiting geological responses to urbanization

City/Region setting	**Geological**	**Dominant geological impact**	**Observed evidence/rate**	**Primary anthropogenic drivers**
Delhi–NCR	Quaternary alluvial plain (Yamuna floodplain)	Land subsidence, aquifer compaction	20-50 mm/yr subsidence (Sentinel-1 PSInSAR, 2014-2020)	Excessive groundwater extraction; urban load; reduced recharge due to impervious surfaces
Ahmedabad (Gujarat)	Semi-arid alluvial terrain, Sabarmati basin	Ground deformation and aquifer compaction	Up to 35 mm/yr subsidence (2020-2023, SBAS-InSAR)	Rapid urban growth; groundwater depletion; industrial pumping
Kolkata (West Bengal)	Deltaic plain of Ganga-Brahmaputra basin	Deltaic subsidence and consolidation	10-20 mm/yr long-term subsidence	Groundwater withdrawal; load from dense built-up area; natural deltaic compaction
Mumbai (Maharashtra)	Coastal alluvium and reclaimed marine flats	Coastal compaction and local settlement	Localised differential settlement (qualitative field evidence)	Land reclamation; load-induced settlement; poor drainage; sea-level rise
Chennai (Tamil Nadu)	Coastal sandy plain and lateritic soils	Saline intrusion and ground lowering	Sea-water intrusion up to 10 km inland; minor compaction	Groundwater over-extraction; coastal urban sprawl; poor recharge
Joshimath (Uttarakhand)	Colluvial slope deposits over weathered schist	Ground subsidence and slope instability	Accelerating ground cracks and structural failure (2021-2023)	Unregulated construction; slope excavation; seepage; weak lithology
Solapur (Maharashtra)	Weathered basaltic terrain (Deccan Trap)	Water-table decline and local compaction	Water-table fall >10 m (1980-2000)	Urbanisation-driven groundwater demand; limited recharge
Kannur (Kerala)	Coastal lateritic terrain	Soil and sediment contamination	Elevated Pb, Zn, Cd in urban soils	Vehicular emissions; industrial effluents; domestic waste

Conclusion

India's rapidly expanding urban systems are no longer passive occupants of the geological environment; they are active geological agents reshaping the near-surface Earth. The synthesis of mechanistic evidence, InSAR-derived deformation trends, groundwater-level decline, slope responses, and geochemical changes demonstrates that urbanisation is fundamentally altering stress fields, sediment behaviour, hydrological pathways, and soil chemistry across diverse geological terrains. Case-study findings from the Bhubaneswar-Cuttack metropolitan region further highlight this transformation; sustained groundwater depletion, widespread impervious cover, and rapid land-use conversion have generated measurable subsidence, enhanced flood susceptibility, thermal intensification, and reduced environmental suitability. Similar patterns in Delhi, Ahmedabad, Kolkata, Mumbai and Joshimath show that these processes are neither isolated nor incidental; they represent a nationwide geological footprint of urban growth.

The evidence underscores that ignoring geology in urban planning has tangible consequences for infrastructure stability, water security, disaster resilience, and long-term environmental sustainability. Incorporating geoscientific knowledge through subsidence monitoring, groundwater regulation, microzonation, urban geological mapping, and geotechnical databases is, therefore, essential for anticipatory planning. Equally, integrating hydrological and geo-mechanical insights with urban design, land-use policy, and climate adaptation can mitigate the cumulative risks of subsidence, slope failure, and soil degradation. Recognising urbanisation as a geological process reframes the responsibility of planners and policymakers; cities are not only built on the ground but actively reshape it. Embedding geological perspectives into governance is thus a prerequisite for resilient, sustainable, and scientifically informed urban futures.

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EARTHY CHRONICLE

Mr. Z. Iqbal

Former Dy. D. G., GSI

13th April 1980 - a fateful day printed in my memory as if it happened just yesterday.

It was my first FSP 1979-80 assignment with GSI, Orissa Circle (South), Bhubaneswar. My colleague, Mr. Somnath Chattopadhyay, and I were assigned to carry out "Geochemical sampling for metallic anomalies in the Similipal Tiger Reserve Forest Area, Mayurbhanj District of Orissa." In those days, it was mandatory to complete 150 days of field work in a single field season in GSI.

In December 1979, we reached Jashipur, the gateway to the Similipal Reserve Forest in Keonjhar District. A jeep and a trailer loaded with essentials for the coming five months of stay in the reserve forest were our assets. From Jashipur to our first campsite at Nawana village in the core zone was about a 40 km journey. We reached the place, kept our basic belongings in the nearby forest guest house, and stayed overnight. The next day we pitched our L tents (for officers), O tent (for the driver), and S and N tents for the kitchen and washroom respectively and established the camp in an open area facing a running stream, from where we could fetch water for our daily needs. By evening, we settled down in the new camp. The following day, we began our fieldwork at the nearest pre-decided sample point. Mandatory information about camp establishment, location, and the monthly work schedule was sent to the Director by post the same evening.

After about two weeks of fieldwork, on a bright winter morning, while preparing for another day, the night chowkidar came running to inform us that a fully grown tiger had visited our camp the previous night while we were asleep. It had come from the riverside, walked between the two L-tents, and moved towards the forest dak bungalow on the hillock behind the camp. Our night watchman always sat at the far end of the camp in a temporary hut, with a fire burning throughout the night to keep warm and safe from wildlife. Mr. Chattopadhyay advised his family to be cautious while we were in the field.

Our next camp, near the Jharonda Falls forest guest house, ended smoothly. Mr. Chattopadhyay then left for Bhubaneswar on another assignment, and his replacement officer was expected to join later. I then shifted to the inner forest area and camped near the Barehipani Falls - my third camp - inside a very wide forest guard campus located on a ridge with 500+ foot-deep falls on two sides, and a two-metre-wide, two-metre-deep ditch around the remaining sides to prevent elephants from entering. Wooden planks were used for entry and exit.

At the end of the fieldwork from this camp, Mr. Rajendra Awasthi joined me in mid-March 1980 to complete the remaining fieldwork. He was accompanied by his wife and toddler daughter. We then shifted to our fourth camp in the deeper inner forest zone, in another ditch encircled forest guard area on the Nawana-Baripada fair weather forest road. There were no pucca roads anywhere in the reserve. We had completed nearly three fourths of our target, but the remaining sampling points lay in dangerous zones inhabited by tigers and elephants. With the onset of summer, water had dried up on the higher hills, forcing wildlife to move towards valleys near streams. Snakes and scorpions had begun emerging from hibernation.

On the fateful day of 13th April 1980, we left our ditch protected camp in the jeep, reached a point on top of the east-west ridge, left the jeep and driver there, and preceded on foot as two groups, one officer with three labourers on either side of the ridge.

After collecting my first sample at the junction of the 1^{st} and 2^{nd} order streams, we moved towards the second sampling location. It was around noon. While leading the team down the slope toward the next point, I was engrossed in studying the toposheet planning for the other sample points. We were walking along a dry nala bed in thick forest when suddenly all the labourers ran to either side. Shocked, I looked back and then forward only to freeze. Just a few meters ahead, a tall, huge tusker stood motionless in the middle of the nala.

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I looked at it, looked back, and found no one behind me. I tried to run, but fear, haste, and the cobbles of the nala made me fall. I got up and tried again, jumping over a dry tree trunk - only to fall face down again. There was no escape.

The elephant, perhaps amazed by my frantic attempts, approached calmly and placed its trunk on me, which felt like a giant wooden log. It slowly wrapped its trunk around my body, and lifted me slightly. At that moment, I thought: "I will be dead within a few seconds, without doing anything worthwhile for my parents who raised and got me educated me with such hardship and meagre means." But divine providence intervened. The elephant dropped me on the fallen tree trunk. I waited for the next move - nothing happened. I looked up and saw the enormous creature running forward, chasing the labourers in the direction where our jeep was parked.

I lay still for several seconds looking towards the elephant and listening to the deafening silence of the forest. When I finally stood up, I moved away from the dead tree and examined myself - cuts on my face, bleeding from the jaw, pain in my chest, and what felt like a cracked or dislocated rib. I began searching for the toposheet, brunton compass, and haversack containing the map, notebook, and lunchbox.

Just then, one of the labourers, who had hidden behind a boulder called out, "Aaggiyaan, haathi chali gala!" ("Sir, the elephant has gone!"). His words reassured me. He suggested that since the elephant had run toward the jeep, we should walk in the opposite direction, toward the forest guard camp (my third camp), protected by the deep ditch.

By then, it was noon. We climbed a ridge on the other bank of the dried-up stream. On the other side of the ridge, there was yet another rolling slope leading to a running stream. The slope had long, lush grass; I wanted to lie down and rest, as the rib pain was now searing. But the labourer advised me not to; as the long stretches of grassland might host a tiger somewhere nearby. Unable to bend and drink myself, the labourer gave me water in a cup made of leaves. We continued walking, crossed the stream, climbed and descended hillocks, and finally reached the forest guard camp by evening. The guard, who knew us from our earlier stay, generously prepared black tea - a priceless gift of comfort at that moment. I broke down in tears after this selfless hospitality. My labourer went to the ranger's residence (our first camp) on foot to seek help. The gentleman arranged a motorcycle and came to me with painkillers. The sun had set by then, and I was at least 10 km away from my current camp.

Meanwhile, when Mr. Awasthi returned to the jeep after his fieldwork, he was shocked to find me missing. Two labourers told him I had been attacked by the elephant and was likely dead. He eventually drove around 20 km via a long route and reached me around 7 pm at the guard camp. We then returned to our current camp. Since it was too dangerous to drive to Baripada hospital (60 km away) at night, we stayed in the camp.

The next morning, I was shifted to the hospital. I stayed for treatment while Mr. Awasthi resumed the fieldwork. . Just two days later, Mrs. Awasthi developed a serious condition in the camp due to her peptic ulcer and was shifted to Baripada hospital immediately. Her ulcer ruptured, and she breathed her last the next night - a greater mishap after the mishap. A heart-broken Mr. Awasthi had to carry her body from Baripada to Bhubaneswar.

Before leaving for Bhubaneswar with his wife's body, Mr. Awasthi waited for the death certificate. I went to the post office to send telegrams to his relatives in Lucknow and to Director Dr. P. K. Banerjee in Bhubaneswar about the sad demise of Mrs. Awasthi. Mr. Awasthi then drove through the night carrying her body for the last rites.

Later, an officer, Mr. T. K. Saha, was sent from Bhubaneswar to close the camp. By then, I had also been discharged from the hospital. Finally, the driver, Mr. Raghu, and I left Baripada in the jeep with the trailer load of field equipment. It took us 24 hours to reach Bhubaneswar, overcoming a few more route-related hurdles.

Thus, the first field season became a memorable but highly painful assignment for me and my colleague.

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SGAT News

61st Meeting of the State Geological Programming Board (SGPB)

The 61st meeting of the State Geological Programming Board (SGPB) was attended online by Dr B. M. Faruque, Shri G. C. Das and Shri G. P. Mohapatra on the 14th of November 2025.

Mineral Development Awareness Programme (MDAP)

MDAP, 2025 was successfully organised from 22 to 24 August 2025 at Joda of Keonjhar district. A record number of 32 teams (16 girls and 48 boys) participated in the event. The participants were from 3 IITs (IIT (ISM), Dhanbad (3 teams), IIT, Kharagpur (2 teams), IIT, Bhubaneswar (2 teams)); 3 NITs (NIT, Rourkela (3 teams), NIT, Jamshedpur (1 team) and NIT, Raipur (3 teams)); Govt. College of Engineering, Keonjhar (3 teams); University of Allahabad, Prayagraj; Andhra University, Visakhapatnam; UCE, Kakatiya University, Kothagudem; AKS University, Satna; IIEST, Shibpur; Jadavpur University, Kolkata; Indian Institute of Science, Education and Research (IISER), Berhampur; MPC Autonomous College, Baripada; Maharaja Sriram Chandra Bhanja Deo University, Baripada; Fakir Mohan University, Balasore; IGIT, Sarang; Utkal University, Bhubaneswar; Ravenshaw University, Cuttack; Sambalpur University, Burla and Dharanidhar University, Keonjhar.

On 21st and 22nd August the participants were received from different bus stops and different trains at Banspani railway station. The participants were accommodated in Mahanadi Guest House, Joda (12 rooms), Yamunotri Guest House, Bileipada (8 rooms), both belonging to Tata Steel; MGM Guest House, Joda (4 rooms); Rungta Guest House, Barbil (4 rooms) and Sarda Mines Guest House, Soyabali (4 rooms).

On 22nd August evening the programme at Valley Club, Joda started with registration, distribution of T-Shirts and self-introduction by participants. The participants were welcomed by Miss Anju Joseph, Geologist, Joda East and Rajesh Kumar, Chief, Joda of Tata Steel; A. B. Panigrahi, Vice-President, SGAT and Shri Abhijit Sen, Sr. Vice-President, Geology, Rungta Sons (P). Ltd. It was followed by the subject specific oral quizzes, which were conducted by Khitish Patnaik, Member, Executive Council, SGAT and J. N. Das, Joint Secretary, SGAT. A. K. Raut, Treasurer, SGAT and M. D. Behera, Member, Executive Council, SGAT assisted in scoring. After the Oraz quizzes were over there was an interactive meet of the participants where the participants demonstrated their extra-curricular activities. The dinner on 22nd August evening was sponsored by Tata Steel.

On 23rd August the participants visited the Joda East Iron Ore Mines of Tata Steel, Tata Steel Sponge Iron Plant, Bileipada (where they had lunch post-visit), Tata Steel Ferro Alloys Plant, Joda and the Water Harvesting Structure. Back at Valley Club, Joda the identification of rocks, minerals, ores, metallurgical products and processes, and mining machineries were carried out jointly by T. Mohanta, J. N. Das, A. K. Rout, M. D. Behera, G. C. Das, Khitish Patnaik and T. K. Rath. The dinner on 23rd August evening was sponsored by Rungta Sons (P) Ltd.

On 24th August the General Round of Oral Quiz was conducted by J. N. Das, who was assisted by T. Mohanta, Khitish Patnaik, M. D. Behera and A. K. Raut.

Before the start of the Valedictory and Prize Distribution Ceremony, the video message of Shri G. S. Khuntia, President, SGAT was displayed for the participants and guests. The message of Shri Khuntia was appreciated by all.

The Valedictory and Prize Distribution Ceremony was graced by Shri Atul Bhatnagar, General Manager, OMQ, Tala Steel and Shri Bramhananda Mahanta, Mining Officer, Joda Mining Circle as Chief Guest and Guest of Honour respectively. Both Shri Mahanta and Shri Bhatnagar, while addressing the students, praised the continuous efforts of SGAT in organising the event

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uninterruptedly over the last 35 years and also highlighted the opportunity the event provides to the participants in gaining the practical field knowledge which otherwise cannot be obtained in class rooms.

In the individual category of identification of rocks, minerals, ores, metallurgical products and processes, and mining machineries the winners were Aditya Ranjan Ojha of the Department of Geology, Maharaja Sriram Chandra Bhanja Deo University, Baripada; Anik Roy of the School of Earth, Ocean & Climate Sciences (Geology Section), IIT, Bhubaneswar and Marumukham Leelakrishna of the Department of Geology, Andhra University, Visakhapatnam among whom there was a tie.

The Department of Mining Engineering, IIT (ISM), Dhanbad represented by Sumit Kumar Bhagat and Ravindra Chandela and the Department of Mining Engineering, NIT, Rourkela represented by P. Bindushree Dora and Kaibalya Prasad emerged as the Overall Third and Second teams of the event respectfully. The Department of Mining Engineering, GCE, Keonjhar represented by Kalyani Behera and Harish Kumar Jena, and the Indian Institute of Science Education and Research (IISER), Berhampur represented by Abhishek Pati and Yuvang Danodia were jointly adjudged the Overall First teams of the event.

The Valedictory and Prize Distribution Ceremony was moderated by T. Mohanta.

After the event, group photographs of the participants, guests and organisers were taken and the participants were sent off by vehicles provided by Tata Steel, MGM Minerals and JSW Steel.

The event was sponsored by Tata Steel and supported by Rungta Sons (P) Ltd., M/s S. N. Mohanty, MGM Minerals Ltd., M/s M. G. Mohanty, M/s KCP Iron (P) Ltd., Sarda Mines (P) Ltd., Jindal Steel and Power Ltd. and JSW Steel Ltd.

The entire programme of MDAP, 2025 was looked after Shri A. B. Panigrahi, Vice-President, SGAT. A lot of feedback from participants as well as HODs of different institutions had been received after the event and these had been forwarded to the sponsors with thanks for information by Shri A. B. Panigrahi.

Lecture #13 of the Distinguished Lecture Series

Lecture #13 of the Distinguished Lecture Series was successfully arranged in hybrid mode at 6:30 p.m. on 23 September 2025. Prof. Raja Venkat Ramani, Prof Emeritus of Mining & Geo-Environmental Engineering, Pennsylvania State University, Penn State, USA delivered the lecture "On Critical Minerals and National Planning". Shri A. B. Panigrahi, Vice-President, welcomed the speaker, Dr Raja V. Ramani and the participants. Shri S. K. Mohanty, Vice-President introduced Dr Raja V. Ramani to all the participants. The lecture of Dr Ramani was very insightful and the different factors determining the criticality of a mineral were highlighted with examples. The question answer session was moderated by Shri Ramanath Praharaj. Shri G. S. Khuntia, President, SGAT gave the concluding remarks on the lecture and presented a memento to Prof. Raja V. Ramani. The participants of the lecture (in both physical and virtual mode) exceeded 100.

Lecture #5 of the Fraternity Presentation (FPP)

The Lecture #5 of the Fraternity Presentation Programme was arranged in online mode at 06:30 p.m. on 15 October 2025. Shri Ramanath Praharaj, Advisor (Mines), Jindal Stainless Ltd. and former Director, Technical (Project & Planning), OMC Ltd., Bhubaneswar delivered the lecture on "Challenges of Underground Mining in Sukinda Valley". The lecture was highly informative and was attended by a number of persons across India.

Visit of Students of Mother's Public School to SGAT

The Mother's Public School, Unit-1, Bhubaneswar had sent a request through email on 14 October 2025 for educational visit of students of Class-X to SGAT. SGAT had accepted the request and requested the school to send the students in two batches. Accordingly, the students of Class X of Mother's Public School visited SGAT on the 6th and 7th of November

2025. On the 6th of November about 70 students accompanied by their teachers visited and on the 7th of November 2025, 56 students visited SGAT. On both the days the students were welcomed to SGAT by Shri T. Mohanta. Shri G. P. Mohapatra briefed the students about SGAT. Shri J. K. Nanda made presentations on the geology, rocks and minerals and Dr. M. Mohanty presented the economic aspect of minerals and showed an animation on Plate Tectonics. Dr. B. M. Faruque apart from showing a video on Continental Drift, talked on the marine geology and its economic importance on 6th November 2025. On 7th November the marine geology and its economic importance was explained by Shri Girija Prasad Mohapatra.

After the presentations the students were sent to the Mineral Museum in the ground floor, where the students were explained about the samples in detail by Shri Jyotiranjan Patnaik, Shri G. P. Mohapatra, Shri G. C. Das and Shri M. D. Behera.

The students and teachers of Mother's Public School were satisfied with the treatment they received at SGAT as was evident from their feedback.

The contributions of Shri G. P. Mohapatra, Shri J. K. Nanda, Dr. Manoranjan Mohanty, Dr. B. M. Faruque, Shri J. R. Patnaik, Shri G. C. Das and Shri M. D. Behera, who made themselves available with a short notice, and their pleasant way of interaction with the students and teachers was praise-worthy.

Regional Environment-cum-Mineral Awareness Programme (REMAP), 2025

The Regional Environment-cum-Mineral Awareness Programme (REMAP), 2025 was completed in the following 8 Mining and Industrial areas of the state.

- Baphlimali-Doraguda
- Ganjam-Chhatrapur-Matikhalo-Berhampur
- Cuttack-Bhubaneswar
- Damanjodi-Panchpatmali
- Gandhamardan-Keonjhar
- Koira-Kalta-Tensa
- Joda-Barbil-Noamundi
- Biramitrapur-Lanjiberna-Gomardih-Rajgangpur

The regional EMAP, 2025 was supported by IREL (India) Limited, OSCOM, Matikhalo; IMFA Ltd., Kaliapani; JSW Shiva Cement, Telighana; NALCO; Utkal Alumina International Ltd.; Rungta Sons Pvt. Ltd.; TRB Mines, Jindal Steel & Power Ltd.; M/s S. N. Mohanty; MGM Minerals Ltd.; Ravindra Vidya Niketan, Keonjhar and OMC Ltd., Suakati.

SGAT Team for the Mineral Development Awareness Programme (MDAP), 2025

T. Mohanta, General Seccretary briefing about MDAP, 2025 to the participants on 22.8.2025

Welcome Address by Miss Anju Joseph, Geologist, Joda East on 22.8.2025

Rajesh Kumar, Chief, Joda, Tata Steel welcoming the participants of MDAP 2025

H. S. Pattanayak, Sr. GM (Mines), MGM Minerals Ltd. welcoming the participants of MDAP, 2025

Mr. Abhijit Sen, Sr. Vice-President (Geology), Rungta Sons (P) Ltd. welcoming the participants of MDAP, 2025

Bramhananda Mahanta, Mining Officer, Joda addressing the participants during the Valedictory Function on 24.8.2025

Participants of MDAP, 2025 ready for field visit on 23.8.2025

Identification of rocks, minerals, ores and metallurgical products on 23.8.2025

Interpretation of Satellite imageries on 23.8.2025

A. B. Panigrahi, Vice-President, SGAT addressing the participants during the Valedictory Function on 24.8.2025

Atul Bhatnagar, GM, OMQ, Tata Steel addressing the participants during the Valedictory Function on 24.8.2025

Abhishek Pati & Yuvang Danodia of IISER, Berhampur receiving the Overall 1st Team Trophy from the guests on 24.8.2025

P Bindushree Dora & Kaibalya Prasad of NIT, Rourkela receiving the Overall 2nd Team Trophy from Atul Bhatnagar, GM, OMQ, Tata Steel

Ravindra Chandela & Sumit Kumar Bhagat of IIT (ISM), Dhanbad receiving the Overall 3rd Team Trophy from Atul Bhatnagar, GM, OMQ, Tata Steel

J. N. Das, Joint Secretary offering the Vote of Thanks to the participants, guests and organisers of MDAP, 2025 on 24.8.2025

Group photograph of the participants, guests and organisers of MDAP, 2025 on 24.8.2025

Prof. Raja V. Ramani receiving a memento after the Lecture #13 of Distinguished Lecture Series on 23.9.2025

Visit of students of Mother's Public School, Unit-1, Bhubaneswar to SGAT on 6.11.2025

➢ News About Members

Dr. D. Srinivasa Sarma, Chief Scientist, CSIR-NGRI, Hyderabad was conferred the **M. Ramakrishnan Gold Medal Award** at the Annual General Meeting of the Geological Society of India on the 7th of October 2025 at Kumaun University, Nainital.

Dr. Y. Rama Murthy and team have won the **Tata Steel Level Innovista** for showcasing the spirit of innovation in the project "Zero-Waste Initiatives For Greener Future" in the Sustainable Impact Innovations Category on October 6, 2025. Dr. Rama Murthy also got the **Certificate of Reviewing** from the Editors of Powder Technology (Elsevier) in recognition of the 25 reviews contributed to the journal between March 2012 and December 2025.

The book **"All About Diamonds in a Nutshell"** authored by Dr. K. Srinivas Rao & **S. V. Satyanarayana** was released by Director General, GSI, on 28 Nov 2025 at GSI, Hyderabad.

➢ New Members

921 **Pravata Kumar Sahoo**
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M/s Geoimage Systems Pvt. Ltd.
Plot No. 768/2888, Malay Vihar
G. G. P. Colony, Rasulgarh
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922 **Dr. Sisir Kanti Mondal**
Professor
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Jadavpur University, Kolkata-700032INDIA

923 **Abinash Sahu**
Manager,
GeologyTata Steel Ltd.
PL 634/2069, Near Shubam Apartments
Hudi Sahi, Joda-758034
Dist.: Keonjhar, Odisha

924 **Prof. Debadutta Mohanty**
Senior Principal Scientist and Head,
Non-conventional Gases Research Group
CSIR-Central Institute of Mining and Fuel Research
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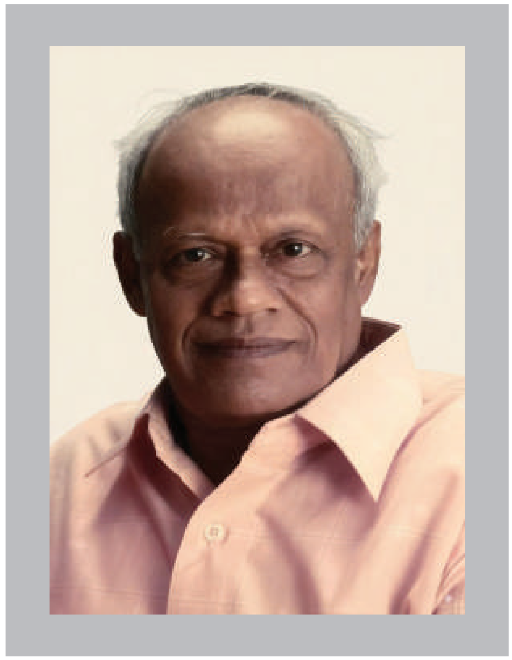
Dhanbad-826 001Jharkhand, INDIA

925 **Dr (Ms) Smruti Rekha Sahoo**
Assistant Professor
Department of Geology
Fakir Mohan University
Nuapadhi, Balasore-756089
Odisha, India

OBITUARY



ANIL KUMAR PAUL
(10.3.1944-20.9.2025)

Prof. Anil Kumar Paul was a distinguished teacher of geology who began his academic career as a Lecturer in Utkal University, Odisha, in February 1966. He rose to the position of Professor in 1978, teaching UG, PG, and M. Phil students, and guiding several Ph.D. scholars as well as mentoring numerous PG and M. Phil dissertations. In addition to his academic contributions, he served the University in several key administrative roles and ultimately became Head of the P. G. Department of Geology in 2001.

Prof. Paul authored seven international and thirty-six national research papers, and presented over forty-five papers and abstracts at various conferences and seminars. His notable publications include the widely used textbook Earth We Live In for +3 Degree Classes, published by D. C. C., Utkal University. He also wrote several pedagogical articles-such as "Harbinger of the Emergence of the Wegenerian Concept," "Why Experimental Petrology?" and "Bulk Monocrystal Growth of Quartz by Hydrothermal Technique"-published in Silalekha, Bulletin of the Geological Seminar, Utkal University, during the 1980s. In addition, he contributed numerous popular science articles in Odia and delivered radio talks aimed at promoting public understanding of earth sciences.

A life member of several reputed earth-science societies, including SGAT, Shri Paul was admired for his humility, clarity of thought, and inspirational teaching methods. His dedication shaped the careers of generations of geology students, who remember him as an exemplary teacher and mentor.

He left for heavenly abode on the 20th of September 2025. The members of SGAT share the grief of his family and respectfully mourn his passing, pay heartfelt tribute to his contributions, and pray for the eternal peace of his noble soul.

Members of SGAT

SUBMISSION OF ARTICLES FOR SGAT BULLETIN
(Instruction to Authors)

Submission of manuscript implies that the same is original, unpublished and is not being considered for publication elsewhere. Each manuscript must be a soft copy of the entire material prepared in Microsoft Word. **Manuscripts in Portable Document Format will not be accepted.** The figures, if any, may be submitted separately in high resolution in JPEG/ TIFF/ BMP format. Both the text files and figures of the manuscript may be submitted by e mail.

Journal Format: **A-4 size**

Language: **English**

Manuscripts: Manuscripts should be computer typed soft copies in double spacing with wide margins in A-4 size (size 12-point Times New Roman font). The title page should include the title of the paper, name(s) of author(s) and affiliation(s). The title should be as brief as possible. An informative abstract of not more than 500 words is to be included in the beginning. Not more than 5 key words are to be listed at the end of the abstract. Text of research papers and review articles should not exceed 4,000 words. The short communication is for quick publication and should not exceed 1,200 words.

Headings: Different headings should be in the following format.

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Illustrations: All illustrations should be numbered consecutively and referred to in the text. They should confirm to A-4 size and carry short captions. Lettering inside figure should be large enough to accommodate up to 50% reduction. Photographs should be of good quality with excellent contrast.

Tables: Each table must be provided with a brief caption and must be numbered in the order in which they appear in the text. Table should be organised within A-4 size and should be neatly typed for direct reproduction. Use of 10 points Times New Roman/ Arial Font for table is recommended. **Tables as pictures will not be accepted.**

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All the manuscripts confirming to the standard format of the bulletin will be reviewed by specialist referees before publication.

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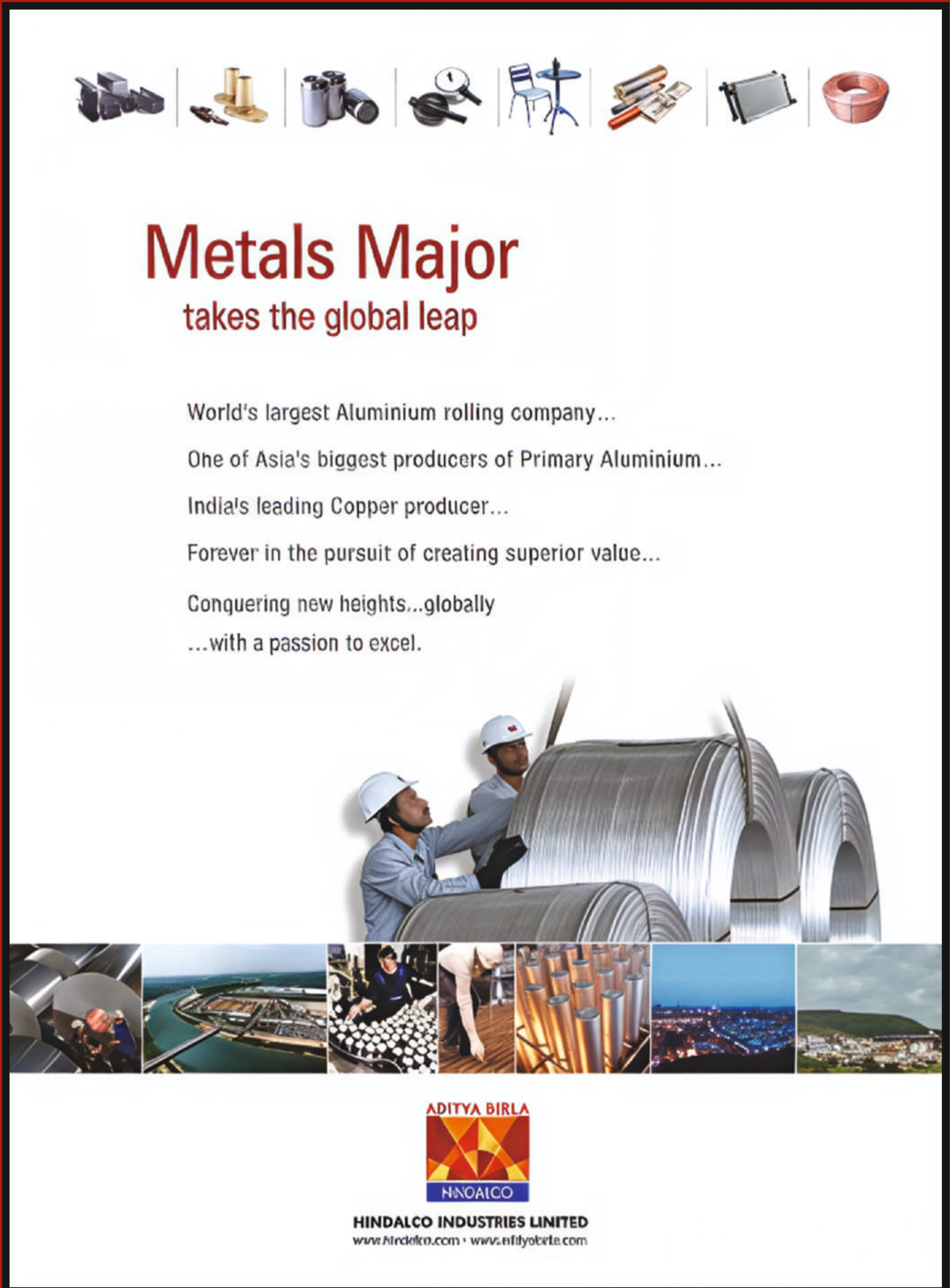
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