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Posted Date: September 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10786638/v1>

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Additional Declarations: No competing interests reported.

Integrated Multi-Frequency Water-Borne Ground-Penetrating Radar Imaging for Bathymetry and Sub-Bottom Stratigraphy characterization of the Kumaun Himalayan Lakes

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Abstract

Lacustrine sediments preserved in the Himalayan region constitute valuable archives for reconstructing Quaternary climate variability, monsoon dynamics, neotectonic activity, and landscape evolution. However, palaeolimnological investigations in the Indian Himalaya have largely relied on direct sediment coring without prior geophysical characterization of lake basins, increasing the risk of recovering disturbed, discontinuous, or incomplete sedimentary sequences. This study evaluates the potential of integrated multi-frequency water-borne Ground Penetrating Radar (GPR) for simultaneous lake bathymetry, sub-bottom stratigraphic imaging, and identification of optimal sediment coring location points in the Lesser Himalayan lakes-Bhimtal and Sattal lakes in the Nainital District, Uttarakhand, India. Water-borne GPR surveys were conducted using complementary 200 MHz and Multi-Low Frequency (16–80 MHz) antenna systems to combine high-resolution imaging of shallow sediments with deeper penetration into basin-fill deposits. The GPR data reveal pronounced variations in lake-floor morphology, sediment thickness, and subsurface architecture, including laterally continuous stratified lacustrine deposits, localized depocentres, erosional surfaces, probable mass-transport deposits, and bedrock-controlled basin margins. The multi-frequency approach effectively distinguished areas characterized by continuous, fine-grained sediment accumulation from zones affected by slope instability and sediment reworking, thereby enabling objective selection of coring locations with the highest potential for recovering long, undisturbed sedimentary records. Comparison of the two antenna systems demonstrates that high-frequency surveys provide superior resolution of shallow depositional features, whereas low-frequency surveys substantially improve imaging of deeper basin architecture and sediment thickness. The results demonstrate that integrated multi-

frequency water-borne GPR provides a rapid, non-invasive, and cost-effective framework for pre-coring investigations in Himalayan lakes. Beyond improving sediment core recovery, this approach establishes an effective methodology for future palaeoclimate, palaeoenvironmental, and geomorphological studies across lacustrine systems of the Himalayan region.

Key Words: Multi-frequency GPR, Lake bathymetry, Lesser Himalayan lakes, Uttarakhand, Sediment coring

1. Introduction

Lacustrine sediments are among the most valuable continental archives for reconstructing past climatic, environmental, and geomorphic changes across a wide range of temporal and spatial scales (Burrough and Thomas, 2009; Kelts and Talbot, 1990; Fritz, 2014; Shen, 2013). Their continuous sedimentary successions preserve integrated records of variations in precipitation, temperature, vegetation, catchment erosion, hydrological processes, and anthropogenic influence, thereby providing critical insights into Quaternary climate evolution and environmental dynamics (Chen et al., 2004). Compared with many terrestrial archives, lake sediments often offer high temporal resolution and excellent preservation, making them particularly suitable for multi-proxy palaeoenvironmental reconstructions. The Himalayan region contains numerous natural lakes that are exceptionally sensitive to variations in the Indian Summer Monsoon, glacial fluctuations, tectonic activity, and catchment processes. Consequently, these lake sediments have become important archives for reconstructing regional palaeoclimate, landscape evolution, and environmental change during the Quaternary. The lesser Himalayan region of the Kumaun sector of Uttarakhand have been studied by several researchers for structure and tectonics (Valdiya 1980, 1988), sediment accumulation (Das et al., 1995), water balance (Kumar et al., 1999a), palaeoclimatic conditions (Kotlia et al., 2000), sediment chemistry (Chakrapani, 2002); trace metals (Puroshatam and Chakrapani 2012); Heavy metals (Das, 2005); Water quality (Inaotombi & Gupta, 2014; Dalakoti et al., 2018; Negi and Singh, 2025; physico-chemical parameters (Joshi et al., 2016) etc.,. Numerous sediment-based investigations from the region have successfully reconstructed changes in monsoon intensity, vegetation dynamics, erosion, and lake hydrology. The reliability of such reconstructions, however, depends fundamentally on recovering long, continuous, and minimally disturbed sediment sequences (Last and Smol, 2001; Cohen, 2003; Fritz, 2014).

Selecting suitable coring locations is therefore a critical step in any palaeolimnological investigation. Sediment cores collected from areas affected by erosion, mass wasting, sediment reworking, or discontinuous deposition may yield incomplete or distorted environmental records, compromising chronological control and palaeoenvironmental interpretation. Despite this, sediment coring in many Himalayan lakes has traditionally been undertaken without detailed characterization of basin morphology or subsurface sediment architecture. As a result, coring locations are commonly selected based on water depth, accessibility, or logistical considerations rather than on the distribution and continuity of sedimentary deposits. This limitation increases the likelihood of recovering disturbed or incomplete sediment sequences and reduces the efficiency of often expensive coring campaigns.

Non-invasive geophysical methods provide an effective means of overcoming these limitations by imaging lake-floor morphology and subsurface sediment architecture before sediment recovery. Among these methods, water-borne Ground Penetrating Radar (GPR) has emerged as a powerful tool for investigating shallow freshwater lakes because electromagnetic waves can penetrate both the water column and underlying sediments under favourable dielectric conditions (Jol and Smith, 1991; Knight, 2001; Moorman, 2002; Neal, 2004; Annan, 2009; Jol, 2009). Water-borne GPR has been widely applied in Europe, North America, and other regions to map lake bathymetry, estimate sediment thickness, identify buried geomorphic features, detect erosional surfaces and mass-transport deposits, and delineate laterally continuous sedimentary sequences suitable for palaeoenvironmental investigations (Moorman and Michel, 1997; Sambuelli and Bava, 2012; Ryazantsev et al., 2021; Lombardi et al., 2022). Compared with conventional bathymetric surveys, GPR simultaneously provides information on both lake-floor morphology and sub-bottom stratigraphy, enabling more informed selection of coring sites.

The performance of GPR depends strongly on antenna frequency. High-frequency antennas provide superior vertical resolution and are well suited for imaging shallow sedimentary structures, whereas lower-frequency antennas penetrate deeper into the subsurface at the expense of spatial resolution (Delaney et al., 2007; Jin et al., 2024). Integrating multiple antenna frequencies, therefore, offers a more comprehensive characterization of lacustrine basins by combining detailed imaging of near-surface sediments with deeper visualization of basin

architecture and sediment thickness. Such an approach has been successfully adopted in several international studies but remains largely unexplored in Himalayan lake systems.

Despite the growing importance of Himalayan palaeoclimate research, the application of water-borne GPR in Indian lacustrine environments remains extremely limited (Mishra, 2023). Most palaeolimnological studies from the Indian Himalaya have relied almost exclusively on direct sediment coring, with little or no prior geophysical assessment of basin morphology or sediment distribution. Consequently, the potential of integrated multi-frequency GPR for identifying optimal coring sites, evaluating sediment continuity, and improving the recovery of high-quality palaeoenvironmental archives has not been systematically investigated. This represents an important methodological gap in Himalayan Quaternary research.

In this study, we apply an integrated multi-frequency water-borne GPR approach using complementary 200 MHz and Multi-Low Frequency (16–80 MHz) antenna systems to investigate the Bhimtal and Sattal lakes of the Kumaun Lesser Himalaya, Uttarakhand, India. The objectives are to **(i)** characterize lake bathymetry and basin morphology, **(ii)** image the shallow and deeper sub-bottom stratigraphy, **(iii)** identify sediment depocentres and evaluate sediment continuity, and **(iv)** determine the most suitable locations for recovering continuous palaeoenvironmental sediment cores. By demonstrating the advantages of multi-frequency GPR for pre-coring investigations, this study provides a practical methodological framework for improving future palaeolimnological and Quaternary research in the Himalayan lake systems.

2. Study Area

The present study was conducted in Bhimtal and Sattal, two freshwater lakes located in the Kumaun Himalaya, Uttarakhand, India (Fig. 1). These lakes form part of the mid-altitude lake system of the Lesser Himalaya and represent important lacustrine archives for investigating Quaternary environmental and climatic change owing to their sensitivity to monsoon variability, catchment erosion, and tectonic activity (Chakrapani, 2002; Joshi and Kotlia, 2015; Diwate et al., 2021). The study area experiences a humid subtropical to temperate climate, with most of the annual precipitation falling during the southwest monsoon (Singh and Bharti, 2018) and is a hub of tourist activity. Seasonal rainfall, steep relief, active hillslope processes and anthropogenic activities strongly influence sediment transport from the surrounding catchments into the lake

basins, promoting continuous sediment accumulation while also generating localized sediment remobilization along basin margins.

Geologically, the lakes are situated within the Lesser Himalayan Sequence, which comprises quartzites, phyllites, slates, schists, and limestones (Valdiya, 1983). The regional geomorphology is controlled by Himalayan tectonics, including thrusts, faults, folds, and fracture systems that have influenced basin development and drainage evolution (Valdiya 1987) Shah and Merh, 1978; Shukla and Bora, 2005; Singh et al., 2024). Weathering of these lithologies supplies both clastic and organic-rich sediments to the lakes, where sedimentation is further influenced by basin morphology, catchment characteristics, and hydrological conditions (Das et al., 1994; Singh et al., 2023).

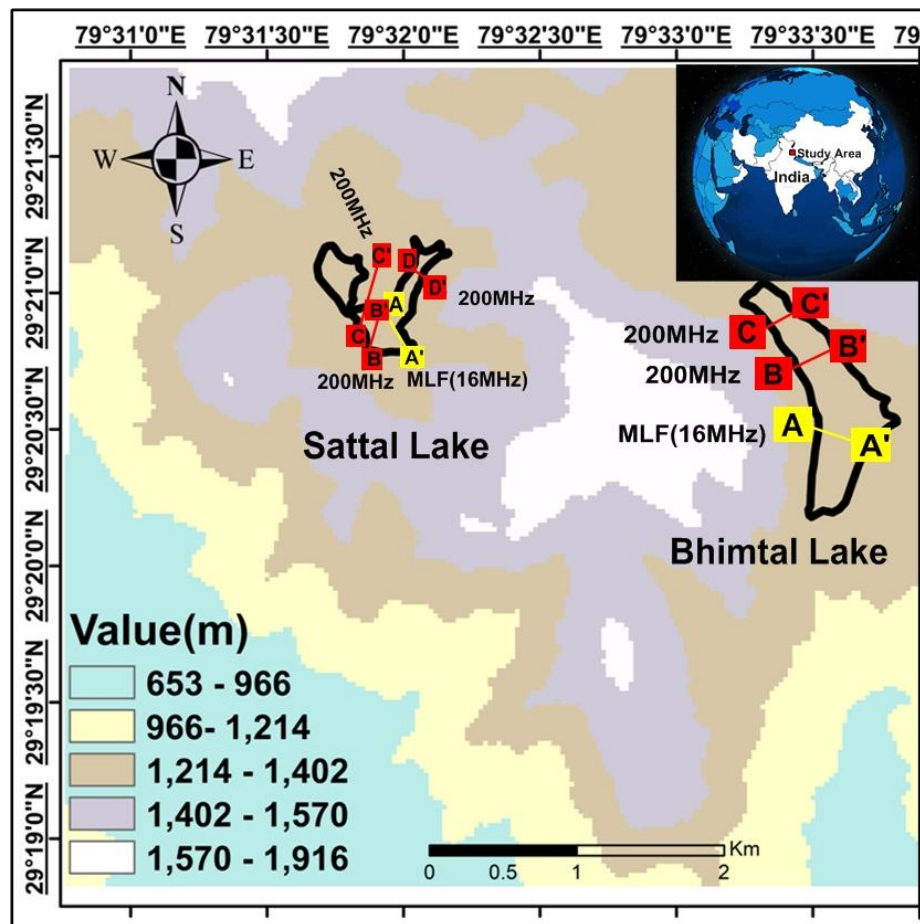


Fig.1. Location map of Bhimtal and Sattal, lakes in Kumaon lesser Himalaya, Nanital, Uttarakhand, surveyed for the bathymetry and Sub-surface Stratigraphic study. The yellow cross-

sections represent a low-frequency MLF antenna for GPR profiles, while the red lines represent a 200 MHz high-resolution antenna.

Bhimtal is one of the largest a natural freshwater lake located in the Kumaun Himalaya of Uttarakhand, India, at an elevation of approximately 1,340 m above mean sea level (Choudhary et al., 2013). The lake occupies an elongated basin where the sediment input is derived primarily from hillslope erosion, seasonal runoff, and small drainage channels. The lake occupies a structurally controlled intermontane basin with relatively deep central and southeastern sectors that act as major sediment depocentres. Lake is surrounded by densely forested hills of the Lesser Himalaya and is primarily fed by perennial springs, seasonal streams, and monsoon runoff. Its origin has been attributed to the combined influence of tectonic activity and geomorphic processes associated with Himalayan uplift (Mathur, 1955). Since its formation, the basin has undergone progressive infilling through the accumulation of sediments derived from the surrounding catchment, preserving valuable archives of regional climatic variability, vegetation change, and catchment evolution (Kotlia et al., 1997), making the lake an important archive of regional environmental change.

Sattal Lake is a complex system of interconnected freshwater basins at similar elevations within a densely forested catchment (Achyuthan et al., 2016). Individual sub-basins differ considerably in morphology, water depth, and sediment accumulation patterns (Singh et al., 2016). Relatively low anthropogenic disturbance and the occurrence of fine-grained, organic-rich sediments in several sectors make Sattal particularly suitable for high-resolution palaeoenvironmental investigations (Choudhary et al., 2009; Chand et al., 2024). Sattal is a freshwater lake system situated at an elevation of approximately 1,370 m above mean sea level in the Kumaun Himalaya, Uttarakhand. Geologically, the lake occupies a structurally controlled intermontane basin developed within the Lesser Himalayan Sequence (Mathur, 1955). The surrounding catchment is characterized by steep hillslopes, weathered bedrock, colluvial deposits, and locally developed alluvial sediments, all of which contribute to sediment delivery into the lake basin (Gururani et al., 2023).

Climatically the study area falls under the south Asian summer monsoon (SASM) regime receiving around 80% of the annual precipitation (1300 to 1500 mm) during summer monsoon months that is June to September (Fig.2). The contrasting basin morphologies, hydrological

settings, and sedimentation patterns of Bhimtal and Sattal provide an ideal natural framework for evaluating the capability of integrated multi-frequency water-borne GPR to characterize lake bathymetry, image sub-bottom stratigraphy, and identify optimal locations for recovering continuous sediment cores.

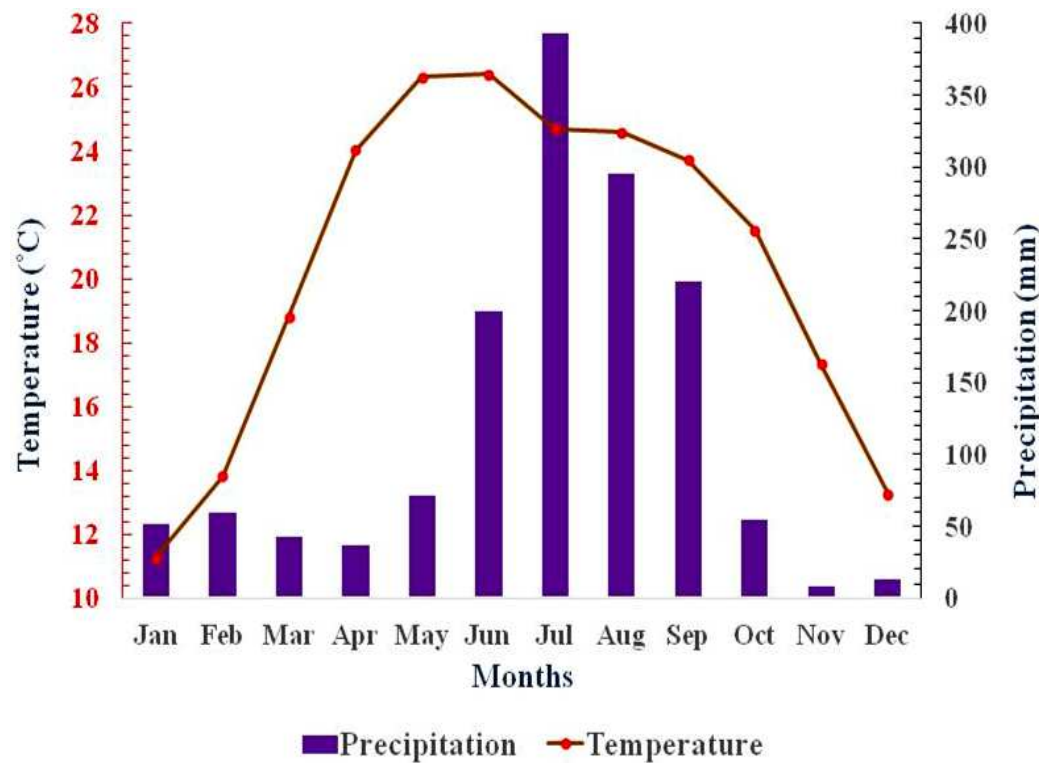


Fig.2. Monthly mean temperature and precipitation of the study area averaged for past 25 years (2000 -2025) Source: CRUv4.07, 0.25x0.25 gridded.

3. Materials and Methods

3.1 Water-borne GPR survey

An integrated water-borne Ground Penetrating Radar (GPR) survey was conducted to characterize lake bathymetry, image sub-bottom stratigraphy, and identify suitable locations for sediment coring in Bhimtal and Sattal lakes. To exploit the complementary strengths of different antenna frequencies, surveys were conducted using both a high-frequency (200 MHz) monostatic antenna and a Multi-Low Frequency (MLF; 16–80 MHz) bistatic antenna. The combination of these systems enabled high-resolution imaging of shallow sedimentary structures while simultaneously improving penetration into deeper basin-fill deposits. The 200 MHz antenna was

primarily used to resolve the water-sediment interface, lake-floor morphology, shallow stratigraphic architecture, and near-surface sedimentary structures. In contrast, the MLF antenna was employed to investigate deeper sedimentary sequences, basin geometry, and major subsurface reflectors that could not be resolved using the higher-frequency system alone (Fig.3). The complementary use of both antenna systems provided a more comprehensive characterization of the lacustrine basins than either system individually.

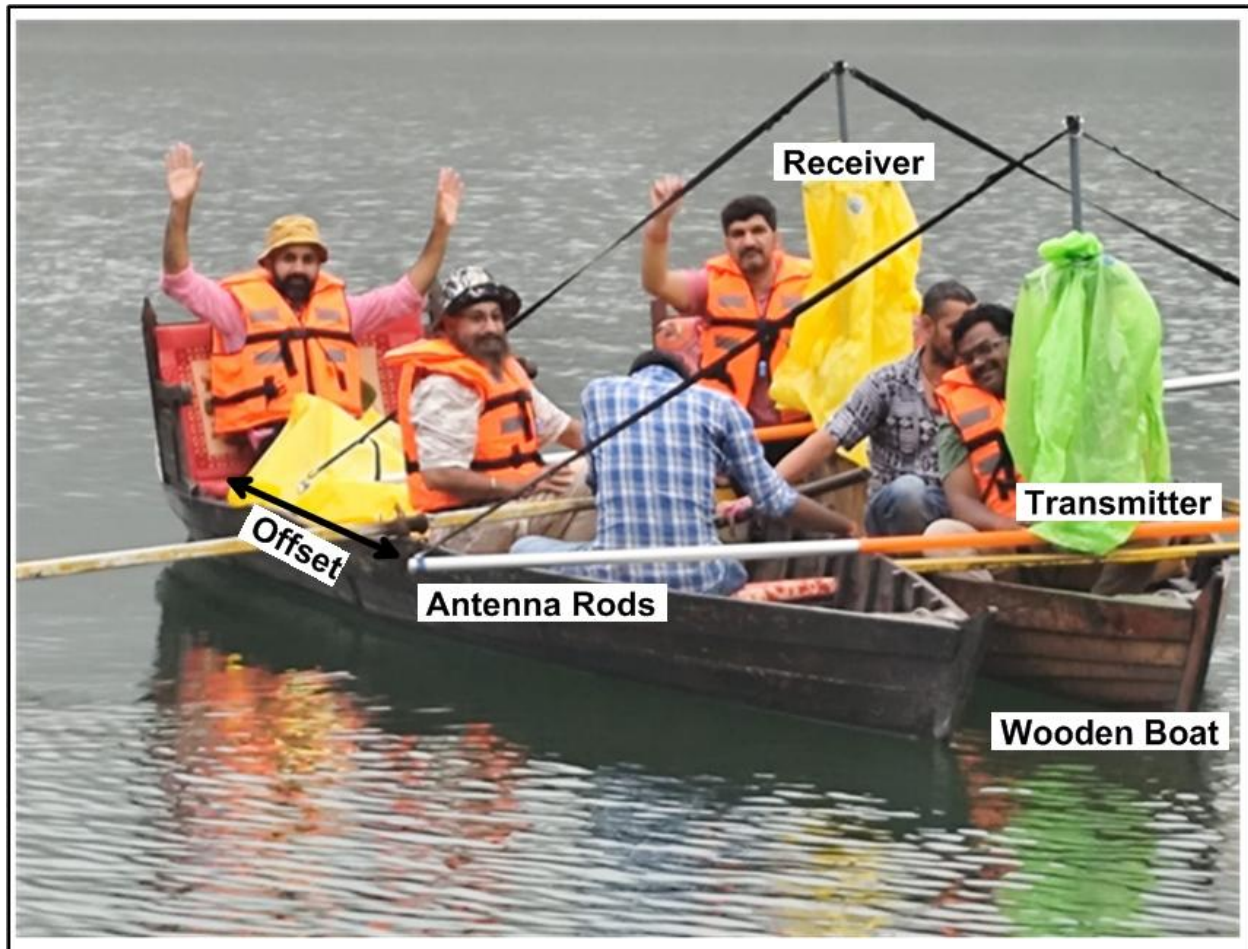


Fig.3. Field photograph showing the GPR data acquisition using multi-low frequency setup at Sattal lake on wooden boats.

3.2 Data acquisition

The GPR surveys were carried out using a GSSI SIR-4000 control unit (Geophysical Survey Systems Inc.), which allowed real-time acquisition and monitoring of radar signals. The 200 MHz antenna was mounted on a wooden survey boat due to its compact size and ease of

operation on the lake surface. In contrast, the physically larger MLF bistatic antenna required two wooden boats to maintain the appropriate transmitter–receiver separation and stable antenna geometry during data acquisition. Survey transects were designed to provide representative coverage of each lake basin by incorporating both longitudinal and transverse profiles (Fig. 1). Profile locations were selected considering lake morphology, shoreline accessibility, water depth, navigation constraints, and the potential suitability of individual basin sectors for future sediment coring. This survey design ensured adequate imaging of both central depocentres and marginal geomorphic features.

3.3 Data processing

Radar data were processed using RADAN 7 software following standard procedures for water-borne GPR data (Jol and Bristow, 2003; Economou et al., 2015). Initial processing included time-zero correction, dewow filtering, background removal, gain adjustment, and trace normalization to enhance reflector continuity and suppress acquisition noise (Maruddani and Sandi, 2019). Subsequent processing involved band-pass filtering, migration, amplitude compensation, and depth conversion to improve image quality and facilitate interpretation of subsurface reflector geometry (Moorman and Michel, 1997; Bostanudin, 2013). These processing steps enhanced the continuity of sedimentary reflections while minimizing artefacts generated during water-borne acquisition.

3.4 Interpretation of radar facies

Processed radargrams were interpreted to identify lake-floor bathymetry, water-column thickness, sediment thickness, reflector geometry, internal stratification, basin morphology, and potential sediment depocentres. The interpretation focused on reflector continuity, amplitude, geometry, and termination patterns, providing insights into sedimentary architecture and depositional processes. Laterally continuous, sub-parallel reflections were interpreted as relatively undisturbed lacustrine sediment accumulation, whereas chaotic or discontinuous reflection patterns were considered indicative of heterogeneous deposits, sediment remobilization, or localized geomorphic disturbance. Areas characterized by thick, continuous sedimentary sequences, minimal evidence of erosion or mass transport, and laterally persistent reflectors were considered the most favourable targets for future sediment coring aimed at high-resolution palaeoenvironmental reconstruction. Overall, the integrated multi-frequency survey provided a

rapid, non-invasive, and cost-effective framework for evaluating basin morphology and subsurface sediment architecture prior to sediment recovery.

4. Results

4.1 Bathymetry and Sub-bottom Characteristics of the Bhimtal Lake

We acquired three representative GPR profiles for the Bhimtal lake using complementary antenna systems (Fig. 1). Profile A–A' was surveyed using the Multi-Low Frequency (MLF; 16–80 MHz) antenna to image deeper basin architecture, whereas Profiles B–B' and C–C' were acquired using the 200 MHz antenna to obtain high-resolution images of the shallow subsurface. The survey layout was designed following a preliminary reconnaissance of the lake and consideration of previous bathymetric investigations (Kotlia et al., 1997; Choudhary et al., 2013; Gururani et al., 2023).

Bistatic Multi-Low Frequency (16–80 MHz) Antenna

The GPR profile A–A' acquired using the Multi-Low Frequency (16–80 MHz) antenna extends approximately 300 m across the lake basin and provides imaging to depths exceeding 40 m, although effective penetration within the saturated sedimentary succession is limited to approximately 20–25 m because of progressive signal attenuation (Fig. 4).

A prominent, laterally continuous, high-amplitude reflector occurs at depths of approximately 4–8 m, clearly defining the water–sediment interface and delineating the morphology of the lake floor. The water column exhibits considerable spatial variability, with depths ranging from about 4 m along the basin margins to nearly 8 m in the central part of the lake, indicating an irregular bathymetry. Below the lake floor, the radargram is characterized by multiple packages of sub-parallel to gently undulating reflections extending to depths of approximately 15–20 m beneath the sediment surface (Fig. 4). These reflector packages display varying degrees of lateral continuity and amplitude, reflecting changes in subsurface stratigraphic architecture. The most laterally continuous and comparatively thicker reflector packages occur between 50–90 m, 130–160 m, and 210–240 m along the profile, suggesting localized zones of enhanced sediment accumulation. At depths greater than approximately 20 m, radar reflections become progressively weaker and less coherent, accompanied by pronounced signal attenuation that

limits interpretation of deeper stratigraphic features. Consequently, the deeper part of the profile is characterized by diffuse reflections with reduced continuity.

Overall, Profile A–A' reveals significant lateral variations in basin morphology and sediment thickness. The presence of thick, laterally continuous reflector packages within the central basin indicates areas of favourable sediment accumulation, which represent promising targets for future sediment coring (Fig. 4).

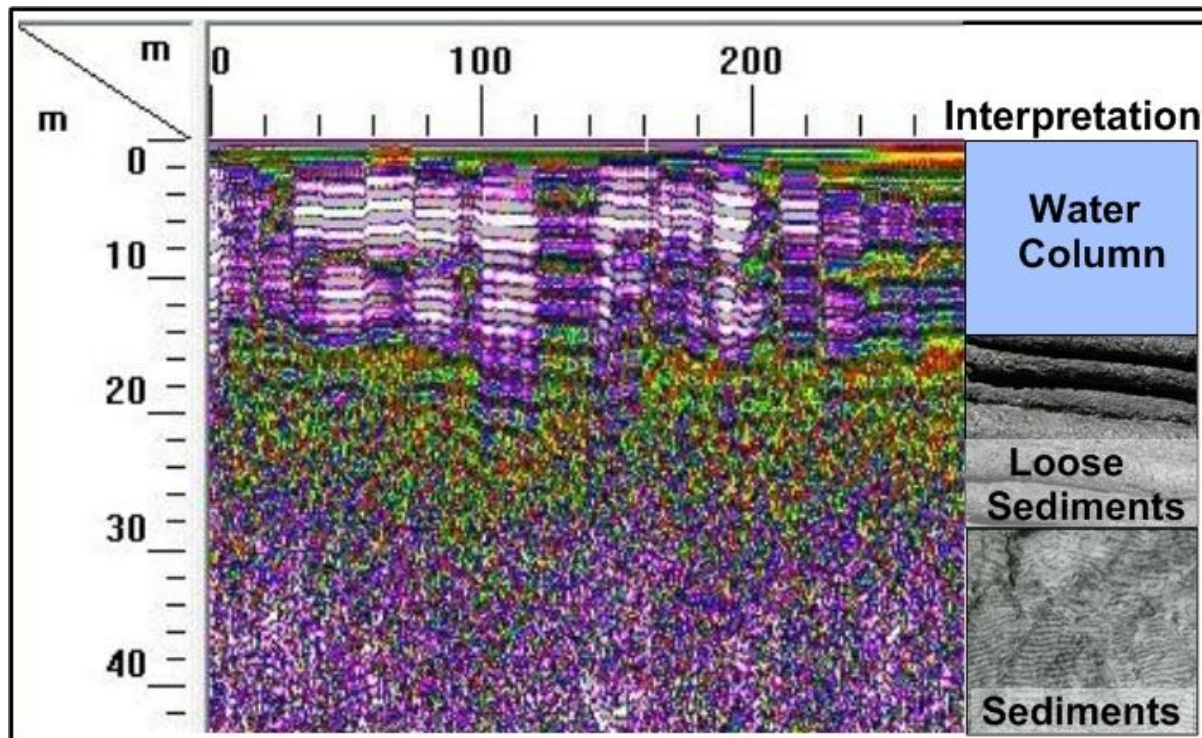


Fig.4. Ground-penetrating radar profile in water along the A-A' transect obtained from the lake using a multi-low frequency (16–80 MHz) antenna placed on a plastic boat. This profile shows the bathymetric profile of the lake bottom and the architecture of the underlying lacustrine sediments. The distinct continuous reflection layer located at depths of ~4–8 m corresponds to the water-sediment interface, indicating the thickness of the water column in the basin. The continuous layers beneath the lake bottom can be treated as stratified sedimentary layers and depocenters suitable for coring.

Monostatic Antenna (200 MHz)

The GPR profile B–B' acquired using the 200 MHz monostatic antenna provides high-resolution imaging of the water column, lake-floor morphology, and shallow sub-bottom sedimentary

architecture (Fig. 5). The profile extends approximately 250 m across the lake and images the subsurface to a maximum depth of about 11 m, providing detailed characterization of the upper sedimentary succession.

A laterally continuous, high-amplitude reflector occurring at depths between approximately 2.0 and 2.8 m marks the water–sediment interface and defines the bathymetry of the lake floor (Fig. 5). The reflector exhibits an undulating geometry, indicating considerable variability in lake-floor morphology along the profile. A pronounced shoaling zone is observed between 90 and 180 m, where the water depth decreases to approximately 1.5–2.0 m, forming a broad submerged ridge or mound. In contrast, the lake floor deepens towards both ends of the transect, where water depths locally exceed 2.5 m. Beneath the lake floor, the radargram displays a succession of laterally continuous to sub-parallel reflections extending to depths of approximately 5–6 m below the sediment surface (Fig. 5). These reflector packages are generally well defined and exhibit consistent lateral continuity across much of the profile, indicating a relatively uniform internal sedimentary architecture. Local variations in reflection amplitude and continuity occur at several locations, producing minor interruptions within the otherwise coherent reflector pattern. Below approximately 5–6 m, the radar signal progressively weakens, and reflections become diffuse and discontinuous owing to increased signal attenuation. Consequently, deeper sedimentary structures cannot be resolved with confidence using the 200 MHz antenna. Among the surveyed intervals, the central part of the profile between approximately 100 and 180 m contains the thickest succession of laterally continuous reflector packages and shows no evidence of major erosional truncation or disrupted internal geometry. This sector, therefore, represents the most favourable location for recovering a relatively continuous sedimentary sequence during future coring investigations (Fig. 5).

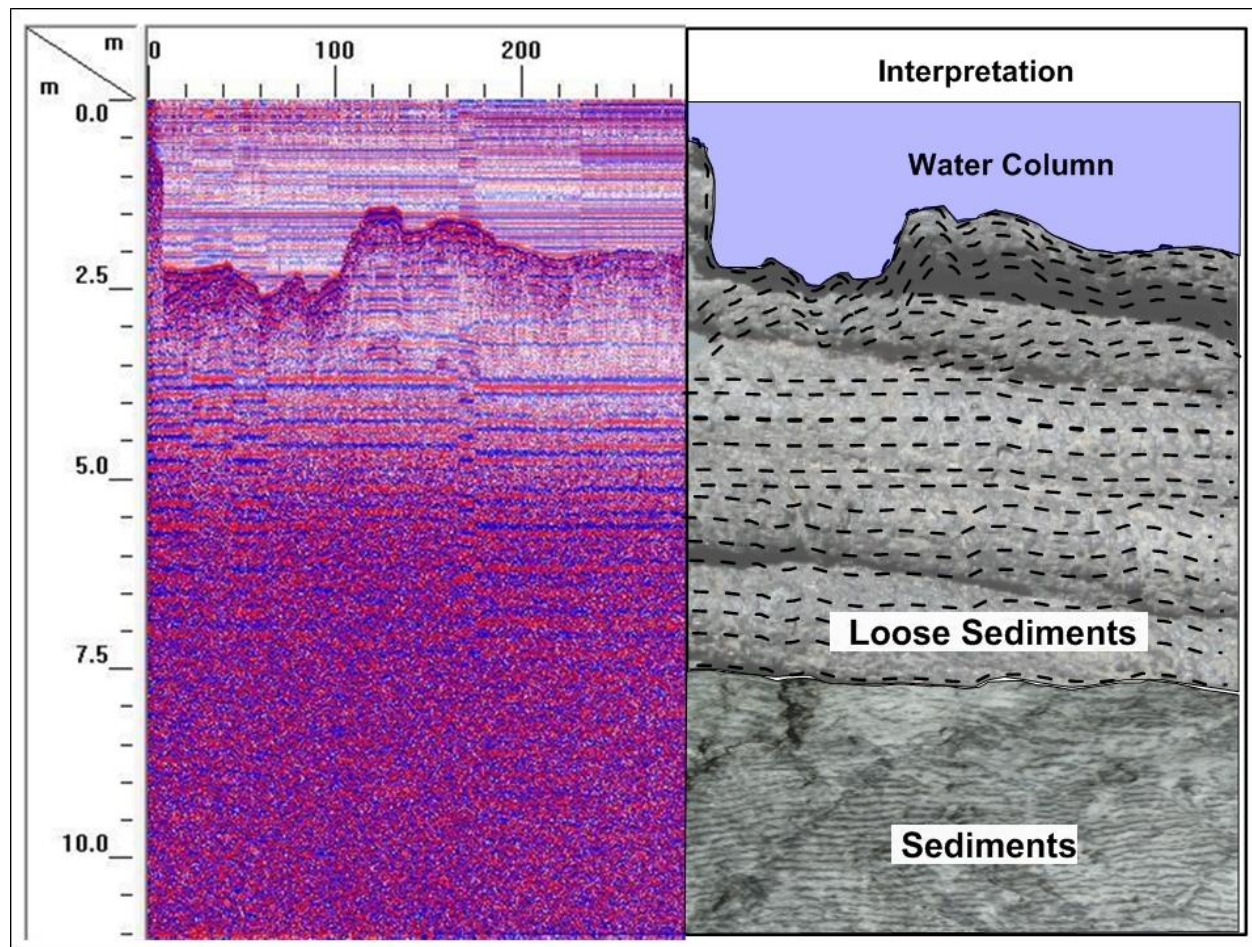


Fig.5. Water-borne GPR section along the cross B-B' recorded in the lake with a 200 MHz antenna attached to a plastic boat. The radargram shows the lake bottom bathymetry and the sedimentary structure below it. The continuous reflector at depths of ~1.5-2.5m corresponds to the water-sediment interface and indicates variability in the water column thickness across the lake. Below the lake bottom, the laterally continuous, high-amplitude reflections represent stratified sedimentary sequences and sediment depocentres where coring can be performed. The thick, undisturbed, and laterally continuous reflections within the 100-180 m range are considered the most promising sites for paleoenvironmental coring.

Profile C–C'

The GPR profile C–C', acquired using the 200 MHz antenna, provides additional information on the bathymetry and shallow subsurface architecture of Bhimtal Lake (Fig. 6). The profile images the water column, lake-floor morphology, and underlying sedimentary succession to a depth of approximately 12 m.

The upper part of the radargram is characterized by a relatively transparent water column bounded below by a strong, laterally continuous reflector corresponding to the water–sediment interface. Water depth varies between approximately 4.0 and 5.5 m, reflecting an uneven lake-floor morphology. Two distinct bathymetric highs are present along the profile: a broad mound in the central part of the transect and a narrower elevated feature towards the right-hand side. These features are separated by comparatively deeper depressions bounded by steeper marginal slopes (Fig. 6). In contrast to Profile B–B', the sub-bottom succession beneath the lake floor is dominated by weak, discontinuous, and locally chaotic reflections. Internal reflector continuity is generally poor, and coherent stratification is only locally developed. Reflection amplitudes decrease rapidly with depth, resulting in strong signal attenuation below the upper sedimentary succession. The contrasting radar facies observed in this profile indicate a more heterogeneous subsurface architecture than that recorded in Profiles A–A' and B–B'. The broad and narrow mounded features are associated with disrupted reflector geometry, whereas the absence of laterally continuous stratification suggests comparatively limited preservation of thick, continuous sedimentary sequences.

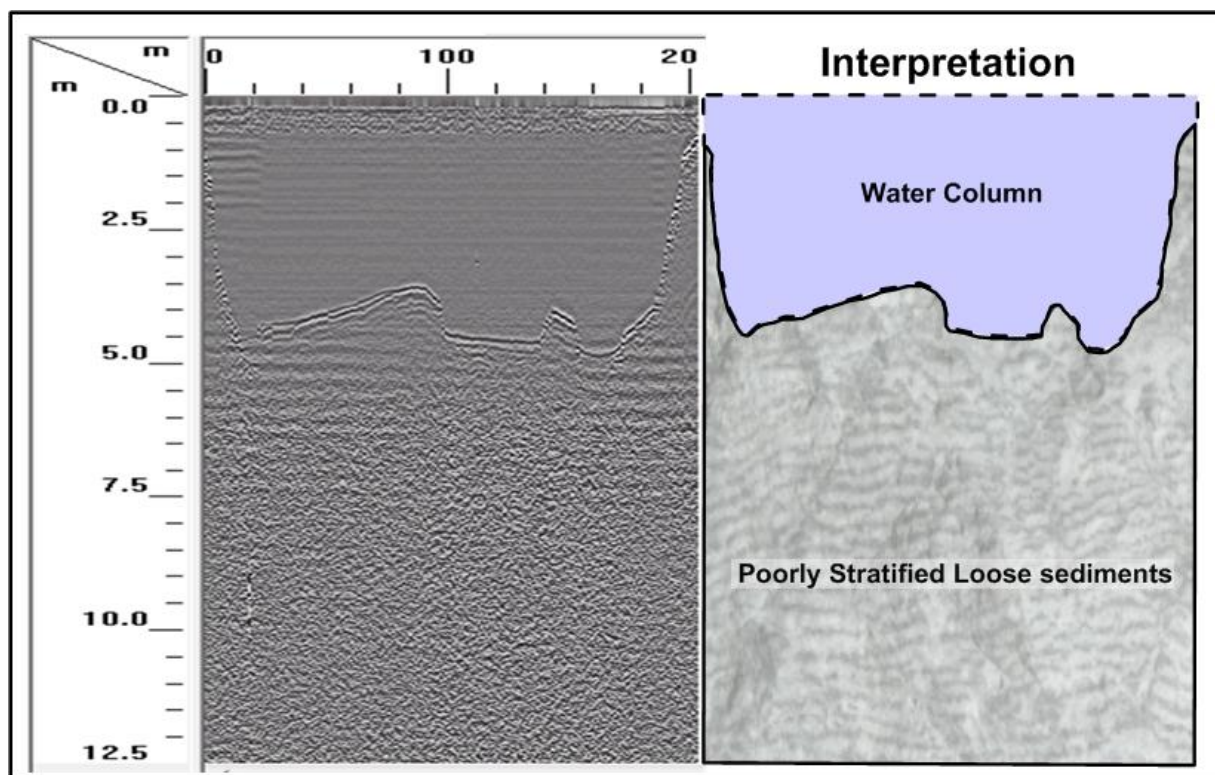


Fig.6. Waterborne GPR data collected for the lake using a 200 MHz antenna from a plastic boat. Radargram clearly shows the water layer, lake floor bathymetry, and sub-bottom sediment structure. The wavy nature of the water-sediment boundary shows varying water depths (~4-4.5m) that indicate the presence of highs and lows in submerged bathymetry, whereas the continuous lateral sub-bottom reflection represents the stratification of lacustrine sediments.

4.2 Bathymetry and Sub-bottom and Sub-bottom Characteristics of the Sattal Lake

To characterize the bathymetry and subsurface stratigraphy, complementary GPR surveys were conducted using both the Multi-Low Frequency (MLF; 16–80 MHz) and the 200 MHz antenna systems. Preliminary reconnaissance surveys were undertaken to optimize antenna selection and survey configuration, following which representative longitudinal and transverse profiles were acquired across the lake (Kotlia et al., 1997; Choudhary et al., 2013).

Bistatic Multi-Low Frequency (16–80 MHz) Antenna (Profile A-A')

The Multi-Low Frequency (16–80 MHz) GPR profile A–A' provides deep penetration into the sedimentary succession and images the overall basin geometry together with the principal subsurface reflector packages (Fig. 7). The radargram extends across the central part of the lake and resolves the water column, lake floor, and deeper sedimentary units.

The upper part of the profile is characterized by a laterally continuous, low-amplitude zone corresponding to the water column, extending from the lake surface to approximately 10 m. A strong, continuous reflector marks the water–sediment interface and defines the morphology of the lake floor. The relatively uniform character of the water column indicates minimal internal radar scattering within the freshwater environment. Below the lake floor, the radargram displays a sequence of well-defined, sub-parallel to gently undulating reflections extending from approximately 10 to 17 m depth (Fig. 7). These reflector packages exhibit good lateral continuity across much of the profile and represent the most coherent stratigraphic interval observed within the deeper sedimentary succession. A prominent, laterally continuous high-amplitude reflector occurs at approximately 18–19 m depth and separates the upper coherent reflector packages from the underlying zone of weaker reflections (Fig. 7). The strong amplitude of this reflector indicates a marked contrast in dielectric properties and probably represents a significant

lithological boundary within the sedimentary succession. However, the precise composition of this horizon cannot be determined from GPR data alone.

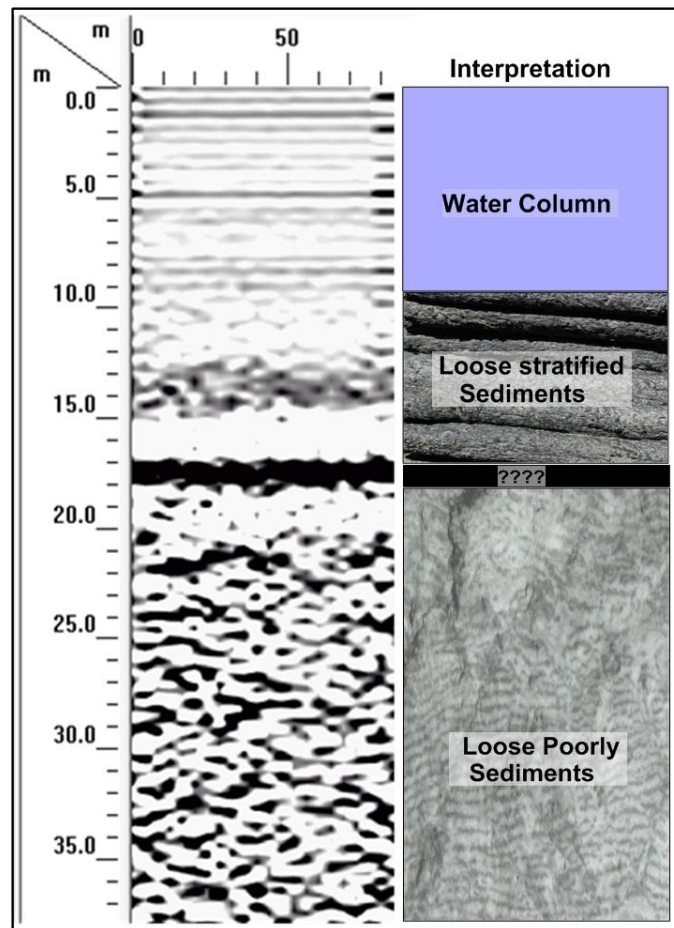


Fig.7. The GPR profile A-A' with 16 MHz MLF antenna indicating the water-sediment interface and sub-surface structures. The profile reveals a layer of water approximately 14-15 meters thick above the lake bottom, followed by a well-stratified sequence of lacustrine deposits. The most notable feature observed at a depth of around 18-19 meters is an anomalous, high-amplitude reflective layer marking the boundary between the upper, well-stratified sediments and the lower, less well-stratified deposits. The deeper sediments reveal a discontinuous reflection pattern, suggesting varied depositional mechanisms.

Monostatic Antenna (200 MHz) (Profile B-B')

The GPR profile B-B' acquired using the 200 MHz antenna provides high-resolution imaging of the shallow sedimentary succession beneath Sattal Lake (Fig. 8). The profile extends approximately 170 m across the basin and images the subsurface to a depth of nearly 10 m,

allowing detailed characterization of lake-floor morphology and the upper sedimentary architecture.

A prominent, laterally continuous reflector occurring between approximately 4.0 and 6.5 m depth defines the water–sediment interface and outlines the bathymetry of the lake floor. The basin exhibits an asymmetric morphology, with a steep western margin where the lake floor deepens rapidly from approximately 1.2 to 4.0 m, followed by a broad, relatively flat central basin maintaining water depths of approximately 4.5–5.0 m. Towards the eastern margin, the lake floor rises abruptly to shallower depths of about 4.0 m, producing a distinct basin asymmetry. Beneath the lake floor, the radargram is characterized by a succession of laterally continuous, sub-parallel reflections extending to depths of approximately 6.5–10 m below the sediment surface (Fig. 8). These reflector packages exhibit good continuity across most of the central basin and represent the most coherent shallow sedimentary succession identified along the profile. Reflection amplitudes decrease progressively with depth, and coherent reflector geometry becomes increasingly diffuse below approximately 5–6 m, where signal attenuation limits further interpretation.

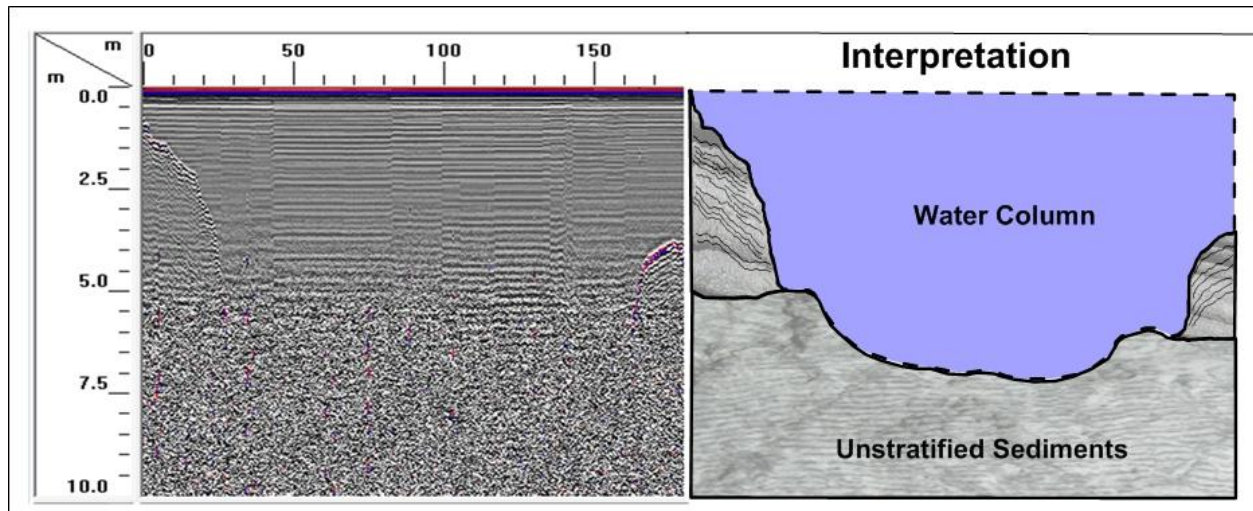


Fig.8. GPR profile along B-B' survey line that displays the water-column thickness, bathymetry of the lake, and sediment structure below the lake bottom. The transparent layer at the top indicates the water column, while the conspicuous layer of the reflector shows the water-sediment boundary. Profile reflects, a wide and flat-bottomed basin with steep marginal slopes,

and sub-parallel to chaotic reflections, below lake bed which are characteristics of weekly stratified to unstratified sediments.

Profile C–C'

The GPR profile C–C' acquired using the 200 MHz antenna provides high-resolution information on lake-floor bathymetry and the shallow subsurface stratigraphy of Sattal Lake (Fig. 9). The profile extends across the central basin and images the upper sedimentary succession to a depth of approximately 10 m.

The upper part of the radargram is characterized by a relatively transparent water column bounded below by a strong, laterally continuous reflector corresponding to the water–sediment interface. Water depth varies markedly along the profile, reaching approximately 8 m within the central basin and decreasing to less than 1 m near the shoreline. This reflector clearly delineates the basin morphology and indicates a broad, gently sloping lake floor with a relatively flat central depocentre. Below the lake floor, the radargram displays moderately continuous, sub-parallel reflections extending through the shallow sedimentary succession (Fig. 9). These reflector packages exhibit good lateral continuity within the central basin but gradually lose coherence with increasing depth owing to progressive signal attenuation. No major erosional truncations, slump structures, buried channels, or other prominent structural discontinuities are evident within the imaged section. The overall reflector geometry indicates a comparatively uniform sedimentary succession beneath the central basin, with continuous reflector packages preserved across much of the profile. The broad, flat-bottomed morphology, together with the relatively coherent internal reflections, suggests favourable conditions for sediment accumulation within this part of the lake. Based on reflector continuity and basin morphology, the central portion of the profile, extending approximately from 1 to 125 m, represents a suitable target for future sediment coring to recover relatively continuous sedimentary sequences (Fig. 9).

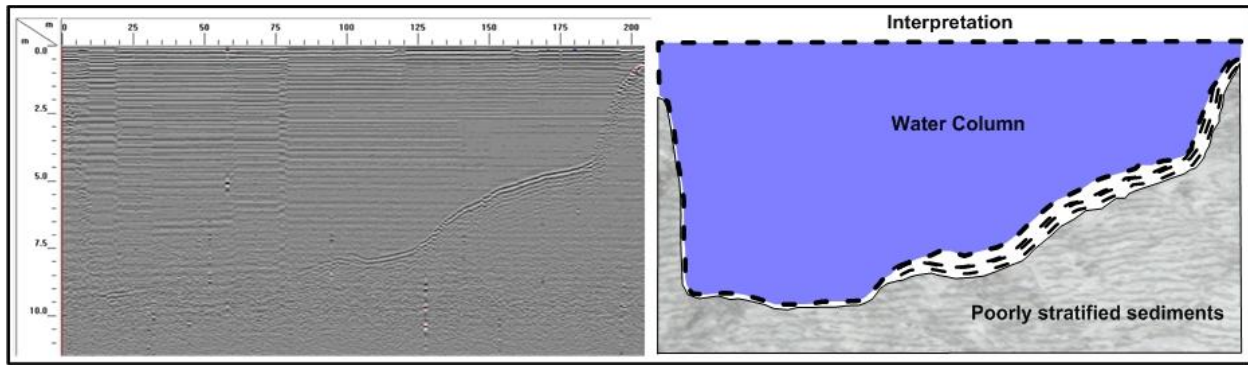


Fig.9. GPR profile along the C-C' survey line using a 200 MHz antenna illustrating the thickness of the water column, lake-floor morphology, and the distribution of poorly stratified sub-bottom sediments. The profile demonstrates lake bathymetry and shallow sediment architecture, providing valuable information for limnological, sedimentological, and paleoenvironmental investigations.

Profile D–D'

The GPR profile D–D', acquired using the 200 MHz antenna, extends approximately 220 m across the eastern sector of Sattal Lake and provides detailed information on basin morphology and shallow subsurface architecture (Fig. 10).

The upper part of the radargram consists of a laterally continuous, high-amplitude zone corresponding to the water column, with water depths ranging from approximately 2.5–3.0 m within the central basin to less than 1 m near the eastern shoreline. The water–sediment interface forms an asymmetric bathymetric profile, characterized by a relatively flat central basin and a pronounced rise towards the eastern margin. Beneath the lake floor, radar reflections are generally weak, discontinuous, and poorly stratified. Unlike the reflector packages observed in the central parts of the lake, this profile exhibits limited lateral continuity and lacks well-developed sub-parallel reflections indicative of thick, stratified sedimentary sequences. Instead, the radargram is dominated by diffuse reflections and scattered signal returns, producing a comparatively heterogeneous subsurface character. A notable feature of this profile is the presence of two prominent inclined, high-amplitude reflectors between approximately 160 and 220 m along the transect (Fig. 10). These reflectors dip towards the basin margin and are interpreted as major subsurface boundaries associated with the bedrock-controlled margin of the lake. The upper reflector likely represents the exposed bedrock surface, whereas the lower

reflector may correspond to a buried bedrock bench or a deeper lithological boundary. The asymmetric geometry of these reflectors suggests that basin morphology is strongly influenced by the underlying geological framework. Below approximately 6–7 m, radar reflections become increasingly diffuse due to progressive signal attenuation, hindering the reliable interpretation of deeper sedimentary units.

Overall, Profile D–D' differs markedly from the other Sattal profiles by exhibiting a thin sedimentary cover, limited internal reflector continuity, and a pronounced bedrock-controlled basin margin. These characteristics indicate comparatively low potential for recovering long, continuous sedimentary sequences, making this sector less suitable for palaeoenvironmental coring than the central basin depocentres identified in Profiles A–A', B–B', and C–C' (Fig. 10).

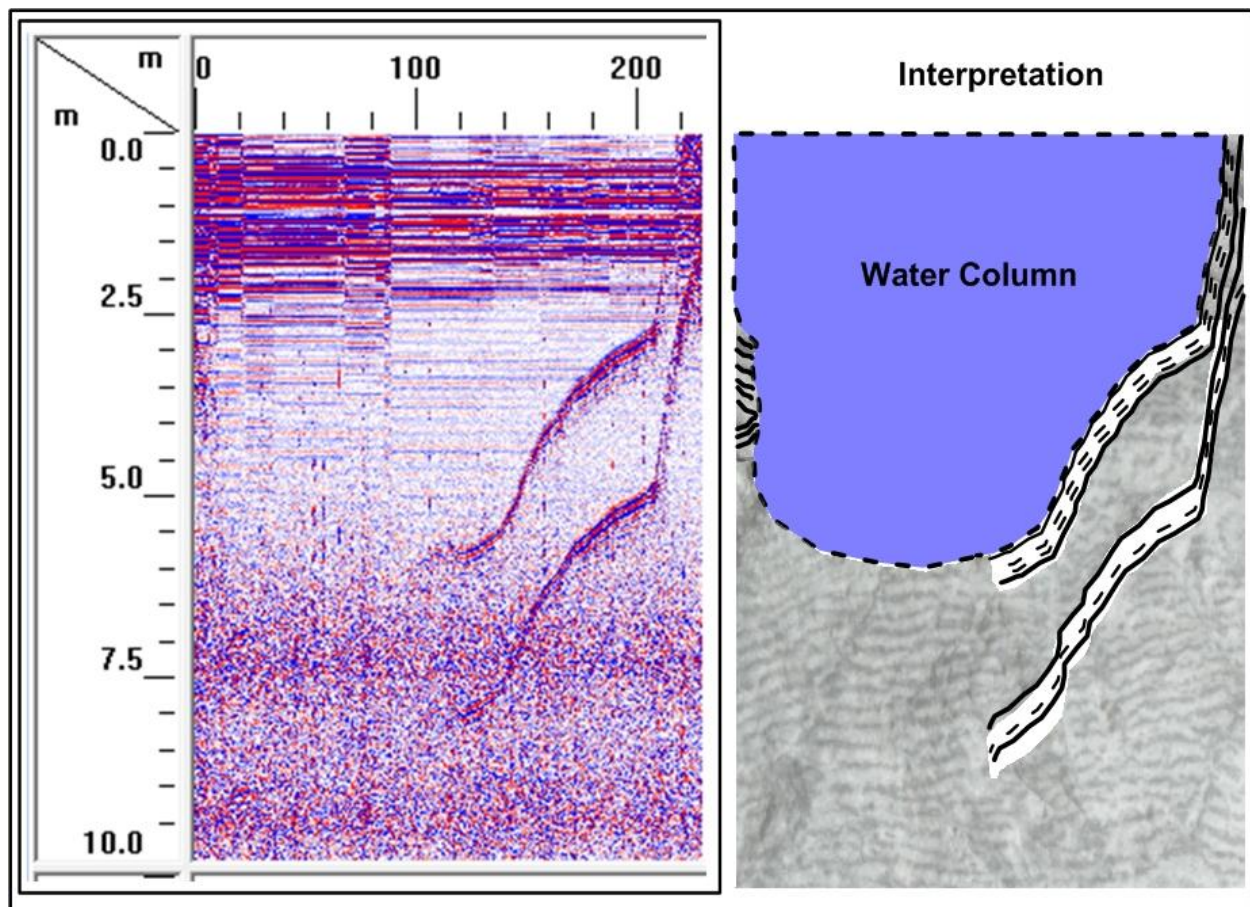


Fig.10. GPR profile along the D-D' survey line using a 200 MHz antenna conducted over the lake with water, bathymetry, and sub-bottom structure indicated. This profile shows an asymmetrical basin with a relatively flat lake floor at the center, which suddenly dips towards the

right basin margin. The sub-bottom structure consists of weak, poorly stratified reflections, suggesting massive or coarse-grained sediments with few internal layers. Strong inclined reflections along the right margin were interpreted as steeply dipping bedrock or a rock-controlled basin margin, while the opposite margin demonstrates a gentler sediment-covered slope. Signal attenuation below approximately 6-7 m makes it difficult to interpret subsurface structures beyond this depth.

4.3 Summary of GPR Characteristics

The integrated multi-frequency GPR survey successfully characterized the bathymetry, basin morphology, and shallow subsurface architecture of both the lakes, Bhimtal and Sattal. The combined application of the Multi-Low Frequency (16–80 MHz) and high-frequency (200 MHz) antenna systems provided complementary information, enabling detailed imaging of both, deep-basin architecture and shallow sedimentary successions. The MLF antenna proved effective in resolving the overall basin geometry and the thickness of the sedimentary succession. In both lakes, the low-frequency signal penetrated considerably deeper than the high frequency signal, enabling identification of major reflector packages, deep sediment accumulation, and basin morphology. In contrast, the 200 MHz antenna provided high-resolution images of the water–sediment interface, lake-floor morphology, and the upper sedimentary succession. The improved vertical resolution allowed detailed characterization of shallow reflector geometry and facilitated identification of localized changes in sediment architecture. Nevertheless, the penetration depth decreased progressively within water-saturated sediments due to signal attenuation, limiting the interpretation stratigraphic units deeper than 10m. Marked differences in radar facies were observed both within and between the two lake basins. Profiles acquired across the central parts of Bhimtal (Profiles A–A' and B–B') and Sattal (Profiles A–A', B–B', and C–C') are characterized by relatively thick sedimentary successions exhibiting laterally continuous to sub-parallel reflector packages. These sectors represent the principal sediment depocentres within the investigated lakes and provide the most favourable conditions for recovering relatively continuous sedimentary sequences. Conversely, profiles located close to lake margins or inlet regions, particularly Bhimtal Profile C–C' and Sattal Profile D–D', exhibit comparatively heterogeneous radar facies characterized by weak, discontinuous, or locally chaotic reflections. These areas are characterized by irregular basin morphology, comparatively thinner sediment

accumulation, and limited reflector continuity, indicating a lower potential for recovering continuous sediment records.

Overall, the integrated interpretation of all GPR profiles demonstrates that basin morphology exerts a primary control on sediment accumulation within both lakes. Broad, gently sloping central basins favour the preservation of thicker sedimentary successions, whereas marginal sectors are characterized by greater spatial variability in reflector geometry and sediment thickness. The combined use of low- and high-frequency antenna systems therefore provides a robust framework for evaluating basin architecture and identifying optimal locations for future sediment coring prior to palaeoenvironmental investigations.

5. Discussion

5.1 Performance of Multi-frequency Water-borne GPR

The integrated use of high-frequency (200 MHz) and Multi-Low Frequency (16–80 MHz) water-borne GPR proved effective for characterizing both lake bathymetry and sub-bottom sediment architecture in the Bhimtal and Sattal lakes. The complementary performance of the two antenna systems enabled simultaneous imaging of shallow sedimentary structures and deeper basin-fill deposits, demonstrating the value of a multi-frequency approach for pre-coring investigations in Himalayan lacustrine environments. The 200 MHz antenna provided superior vertical resolution and clearly resolved the water–sediment interface, shallow reflector geometry, and variations in lake-floor morphology. These data were particularly useful for identifying subtle bathymetric features, recent sedimentary structures, and the spatial distribution of near-surface sediment packages. However, the penetration depth decreased rapidly beneath conductive, water-saturated sediments due to signal attenuation.

In contrast, the Multi-Low Frequency antenna substantially increased penetration depth and allowed imaging of deeper sedimentary packages, basin geometry, and major subsurface reflectors that were not visible on the high-frequency profiles. Although vertical resolution was comparatively lower, the additional penetration provided important information on sediment thickness and basin architecture that is essential for evaluating the suitability of coring sites.

The MLF (16–80 MHz) antenna penetrated beyond 40 m, although significant reflections were mainly obtained from the upper 20–25 m because of attenuation within the water-saturated sediments (Fig.11). Nevertheless, the lower-frequency antenna successfully imaged multiple laterally continuous reflection extending to depths of around 15–20 m beneath the sediment surface (Fig.11). These deeper reflections signify successive depositional units produced during different stages of lake evolution. The complementary strengths of the two antenna systems demonstrate that integrated multi-frequency surveys provide a more complete representation of lacustrine sedimentary architecture than single-frequency investigations. Similar advantages have been reported in freshwater lake studies from Europe and North America (Sambuelli et al., 2009; Ryazantsev et al., 2021; Lombardi et al., 2022), indicating that the methodology is equally applicable to Himalayan lake systems.

5.2 Sedimentary Architecture and Basin Evolution

The GPR data reveal pronounced spatial variability in sedimentary architecture within both lake basins, reflecting differences in basin morphology, sediment supply, and depositional processes. Laterally continuous, sub-parallel reflector packages observed mainly within the deeper central basins indicate relatively stable sediment accumulation, whereas discontinuous or chaotic reflections are concentrated near lake margins and inlet sectors where sediment delivery and geomorphic disturbance are likely to be greater. These contrasting radar facies suggest that sedimentation within the two lakes is strongly controlled by basin morphology.

At Sattal lake, we observed the deepest water column along the Profiles A-A', and B-B' at the centre of lake where the lake bottom lies upto the depth of approximately 10m and 8m respectively. The profile D-D' exhibits shallowest conditions with the lake bottom ranging between 2.5m to 3.0m and as lower as 1m towards the eastern shoreline. The GPR image clearly reflect that the central basin forms the principal sediment accommodation zone, whereas the marginal sectors are characterized by relatively shallow water and greater influence of bedrock topography. Furthermore, the central basin reflects relatively flat floor with gentle gradient having comparatively steeper margins. In the western margin we observed a steep gradient (Profile B–B'), where the lake floor deepens rapidly from approximately 1.2 m to nearly 4.0 m, suggesting structural or lithological control on basin development. Conversely, the eastern margin represent (Profile D–D') a pronounced rise associated with inclined bedrock surfaces, that

suggest the morphology as primary factor rather than sediment accumulation. At the centre of the basin (MLF profile A-A') reveals consistent reflections that extend from the lake floor at approximately 10 m depth to nearly 17 m, indicating a sediment thickness of approximately 7m (Fig.11). Beneath this succession, a laterally continuous, high-amplitude reflector marking a major dielectric contrast at approximately 18–19 m, represents a significant lithological boundary separating lacustrine sediments from the underlying basin substrate or weathered bedrock (Fig.11). The high-resolution 200 MHz profiles further refine the interpretation of the upper sedimentary succession. In Profile B–B', laterally continuous sub-parallel reflections extend from the lake floor to approximately 6.5–10 m below the sediment surface, indicating a well-preserved sequence of shallow lacustrine deposits (Fig.11). From a palaeoenvironmental perspective, the central basin represented by Profiles A–A', B–B', and C–C' offers the greatest potential for recovering long, continuous sediment cores.

The GPR Profiles of Bhimtal lake show considerable spatial variability ranging from approximately 4 to 8 m, with the deepest part occurring in the central basin as reflected by the MLF profile A–A'. The 200 MHz Profile B–B' records water depths of approximately 1.5–2.8 m with submerged ridge like topography reflecting comparatively shallower water column whileas, the Profile C–C' reflects intermediate water depths ranging from 4.0 to 5.5 m, with prominent bathymetric highs separated by deeper depressions (Fig.11). These variations collectively demonstrate that the morphology of Bhimtal Lake bottom is highly irregular.

Central depocentres favour the preservation of thicker sedimentary successions under comparatively low-energy depositional conditions, whereas marginal environments are more susceptible to sediment reworking through slope failures, debris transport, or episodic inflow events. Similar relationships between basin morphology and sediment preservation have been documented in numerous lacustrine environments worldwide (Buynevich and Fitzgerald, 2003; Arcone et al., 2010). Several profiles also reveal asymmetrical basin geometry and steep bedrock-controlled margins, particularly within Sattal Lake. These observations indicate that inherited geological structure has influenced basin morphology and, consequently, the spatial distribution of sediment accumulation. However, confirmation of structural controls requires integration with geological mapping and sediment-core evidence, and therefore the present interpretations should be regarded as preliminary.

5.3 Implications for Coring

One of the principal outcomes of this investigation is the identification of sediment depocentres with the highest potential for recovering continuous palaeoenvironmental records. Radar profiles demonstrate that the most suitable coring locations are characterized by thick sedimentary packages, laterally continuous reflector geometry, limited evidence of erosion or sediment remobilization, and favourable basin morphology. In contrast, profiles acquired near steep basin margins and lake inlets commonly display discontinuous or chaotic reflections, suggesting heterogeneous sediment accumulation and a greater likelihood of disturbed sedimentary sequences. Although GPR cannot independently determine sediment composition or chronology, it provides a robust framework for identifying sites where the probability of recovering long, continuous sediment cores is substantially increased. Consequently, integrating geophysical surveys prior to coring can improve sampling efficiency, reduce drilling uncertainty, and enhance the quality of palaeoenvironmental reconstructions. This is a key methodological advance because most Himalayan lake investigations have traditionally relied on coring strategies based primarily on bathymetry or logistical accessibility rather than on subsurface sediment architecture.

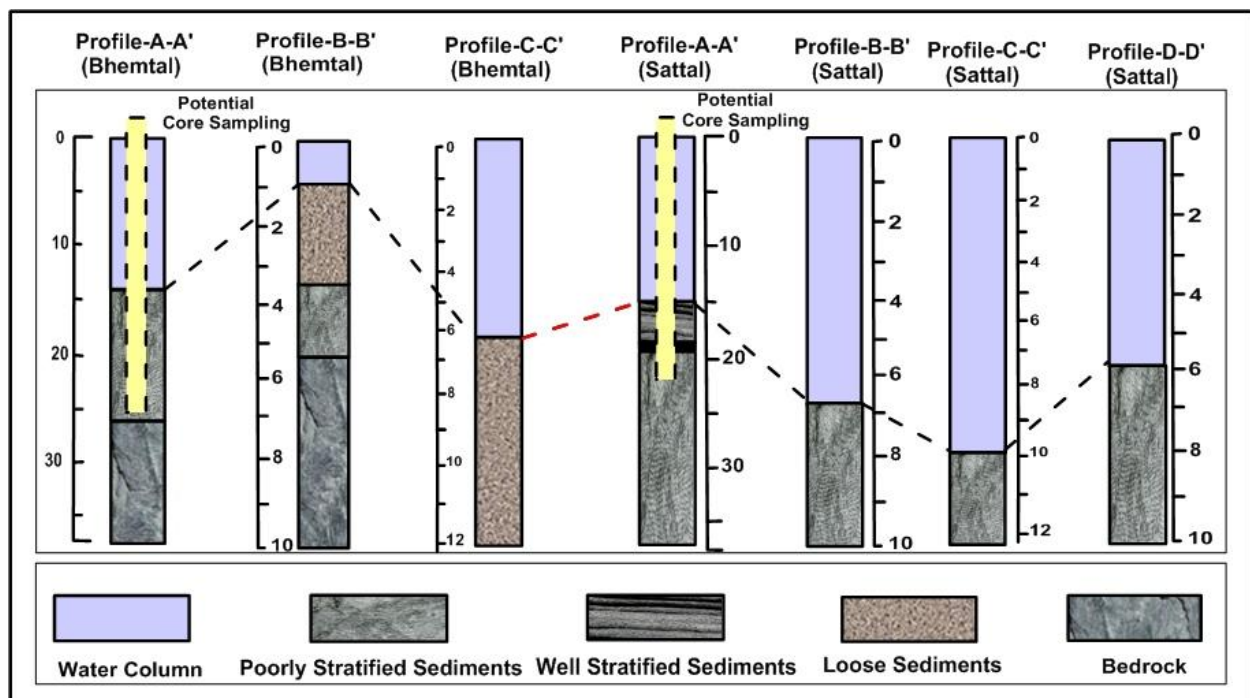


Fig.11. GPR cross-sections of Bhemtal and Sattal lakes representing multifrequency-multi resolution results of 07 profiles taken across the lakes. The yellow coloured dashed lined region represent the potential coring sites to achieve the maximum thickness of stratified sediments for various future studies.

5.4 Broader Significance

The methodological framework presented here has implications beyond the Bhimtal and Sattal lake systems. Numerous Himalayan lakes preserve long Quaternary sedimentary records that have been widely used to reconstruct monsoon variability, tectonic activity, vegetation history, and landscape evolution. However, many of these investigations have been undertaken without detailed geophysical characterization of basin morphology and sediment distribution prior to coring. The present study demonstrates that integrated multi-frequency water-borne GPR provides an efficient and transferable approach for improving core-site selection across Himalayan lacustrine systems. By combining bathymetric mapping with sub-bottom stratigraphic imaging, the method enables identification of continuous sediment depocentres while avoiding areas affected by erosion, sediment reworking, or slope instability. Adoption of this approach has the potential to improve the quality of sediment archives recovered for future palaeoclimate, palaeolimnological, and Quaternary investigations throughout the Himalaya.

5.5 Limitations

Despite its advantages, there also exists several limitations in such studies where careful data acquisition and knowledge of site characteristics are an essential component of survey. The most basic constraint involved in the water borne GPR survey is an increase in the attenuation of signal that reduces the depth of investigation. The attenuation may be caused by the conductivity of water, variation in the dissolved ions and the suspended material like clay. The complex morphology of Himalayan lakes with sudden change in water depths and steep basin margins may also cause diffraction, side reflections and geometric distortion. In addition, the boat motion and antenna coupling, may also introduce acquisition artefacts that locally influence reflector continuity. The data interpretations presented in such studies also need validation with the existing bathymetry maps of the lakes to accurately target the sub-bottom stratigraphy for sediment core targeting.

6. Conclusions

This study demonstrates the effectiveness of integrated multi-frequency water-borne Ground Penetrating Radar (GPR) for simultaneous lake bathymetry, sub-bottom stratigraphic imaging, and identification of optimal sediment coring sites in the Bhimtal and Sattal lakes of the Kumaun Himalaya. The complementary application of the 200 MHz and Multi-Low Frequency (16–80 MHz) antenna systems enabled detailed characterization of both shallow sedimentary structures and basin architecture, illustrating the advantages of combining high-resolution imaging (200 MHz antenna) with greater depth penetration (16–80 MHz antenna). The GPR surveys revealed pronounced spatial variability in basin morphology and sedimentary architecture within both lakes. Laterally continuous reflector packages were predominantly observed within central basin depocentres, whereas discontinuous or chaotic reflections occurred mainly near lake margins and inlet zones. These contrasting radar facies indicate significant variations in sediment accumulation and preservation potential across the lake basins and provide an objective basis for evaluating the suitability of coring locations. The results demonstrate that integrating bathymetric mapping with sub-bottom stratigraphic imaging substantially improves pre-coring assessment by identifying sectors most likely to preserve long, relatively undisturbed sedimentary sequences while avoiding areas affected by sediment remobilization, erosion, or complex basin morphology. Although GPR alone cannot determine sediment composition or chronology, it provides a robust geophysical framework for optimizing sediment recovery and increasing the likelihood of obtaining high-quality palaeoenvironmental archives. Beyond the investigated lakes, this study establishes a transferable methodological framework for future palaeolimnological investigations across Himalayan lacustrine systems. Incorporating multi-frequency water-borne GPR into pre-coring surveys has the potential to improve sampling efficiency, reduce uncertainty during drilling campaigns, and enhance the quality of core sampling for Quaternary palaeoclimate reconstructions.

Acknowledgements

The authors gratefully acknowledge the Ministry of Earth Sciences (MoES), Government of India, for providing the Ground Penetrating Radar (GPR) system under the research project entitled "Seismic Hazard Assessment in the Kashmir Himalaya, using geological, seismological and geodetic data" which made this investigation possible. The study was conducted as a part of

the Quaternary Lake drilling Programme of Birbal Sahni Institute of Palaeosciences, Lucknow. The authors are also thankful to the Prof. M G Thakkar, Director, Birbal Sahni Institute of Palaeosciences, Lucknow for the institutional support, and for providing the necessary facilities to carry out this research successfully. The Ministry of Earth Sciences is highly acknowledged for the GPR instrument.

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